

# Twilight at the Tevatron

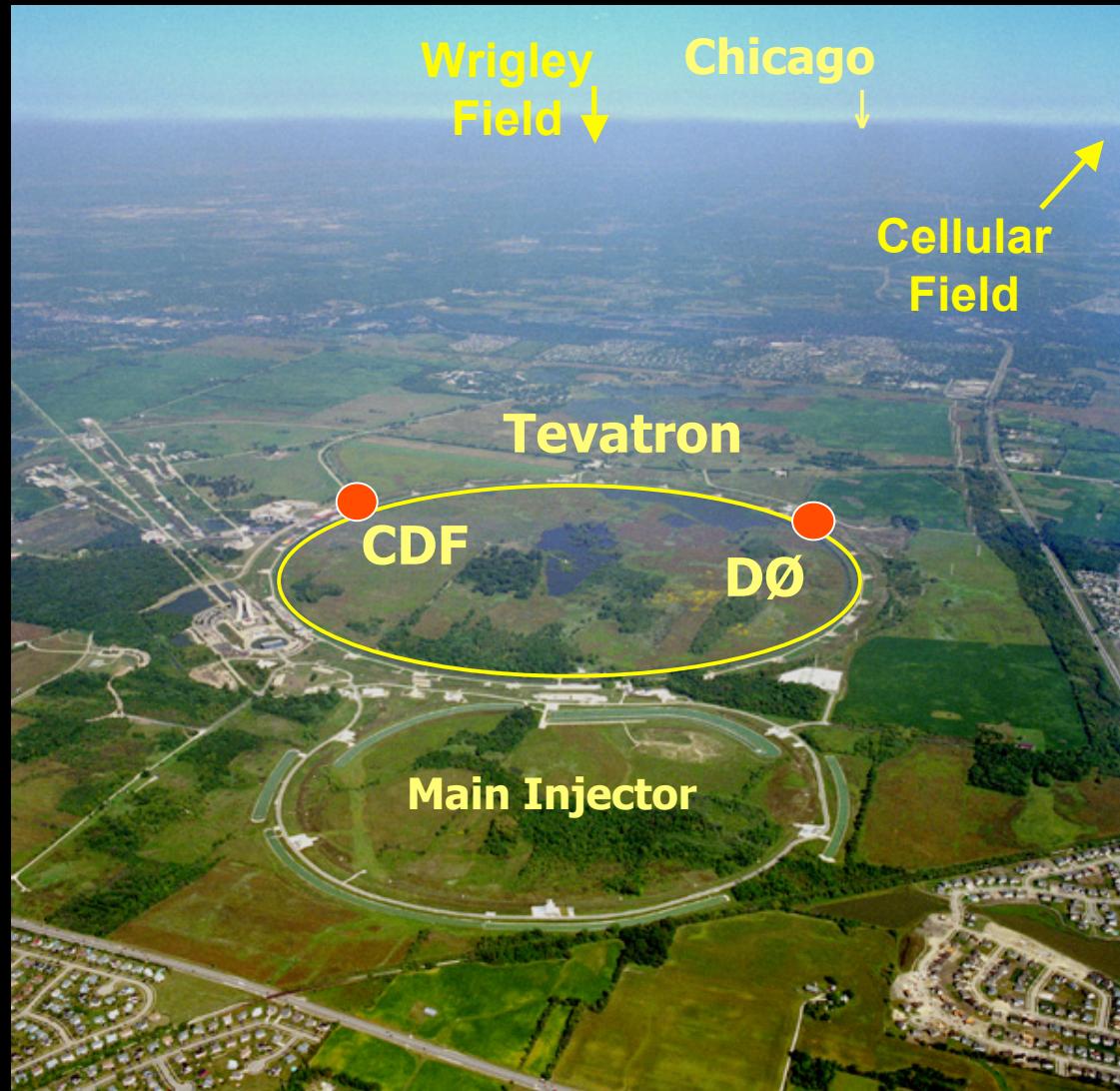
...

D.Genzinski  
Fermilab  
09.02.12

# Backdrop

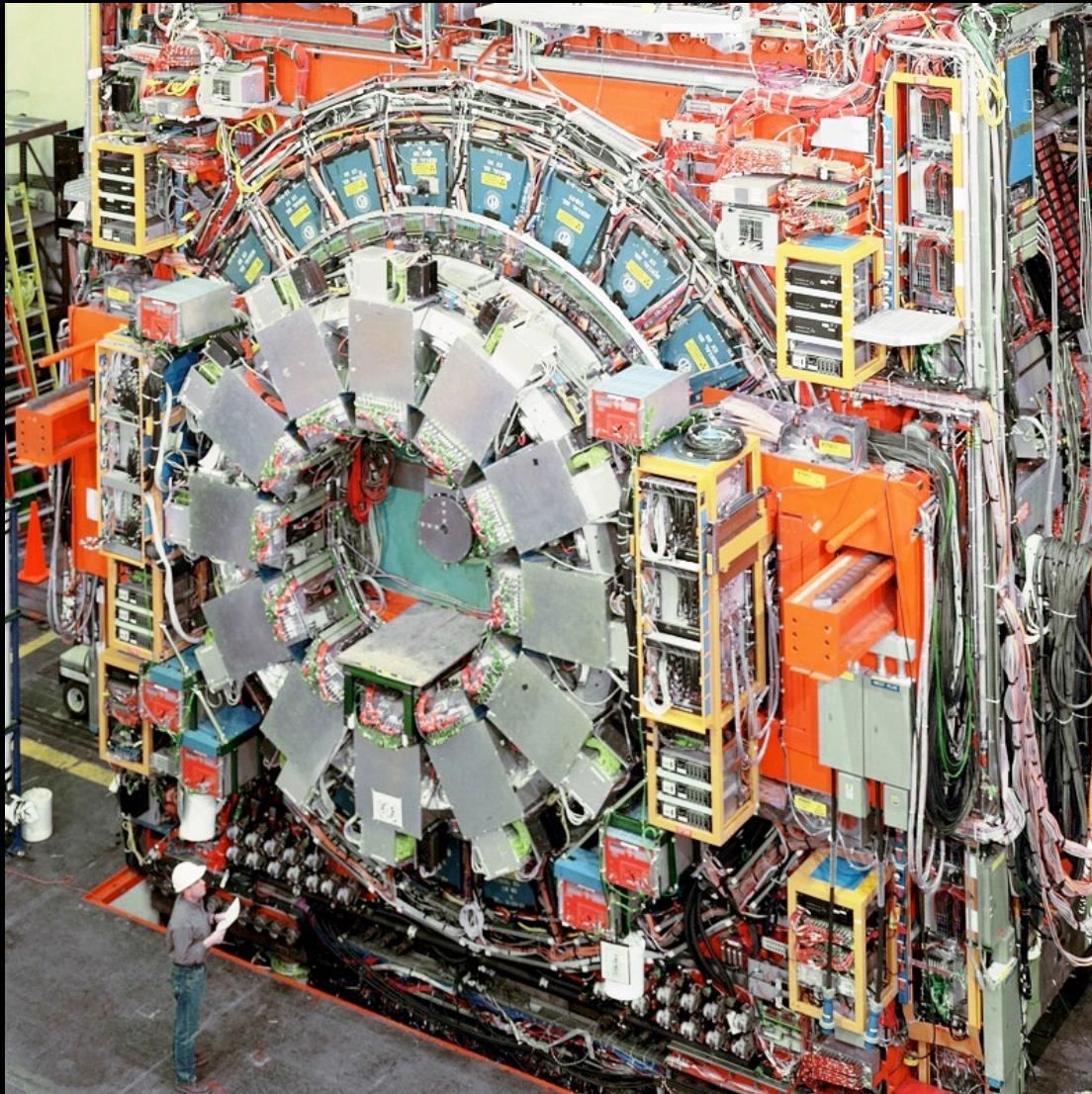
- Fermilab's Tevatron
  - Proton/Anti-proton Collider at  $E_{cm}=2$  TeV
  - World's Most Powerful Collider for last 25 years
  - Home to two Large Experiments (CDF, D0)

# Fermilab Tevatron



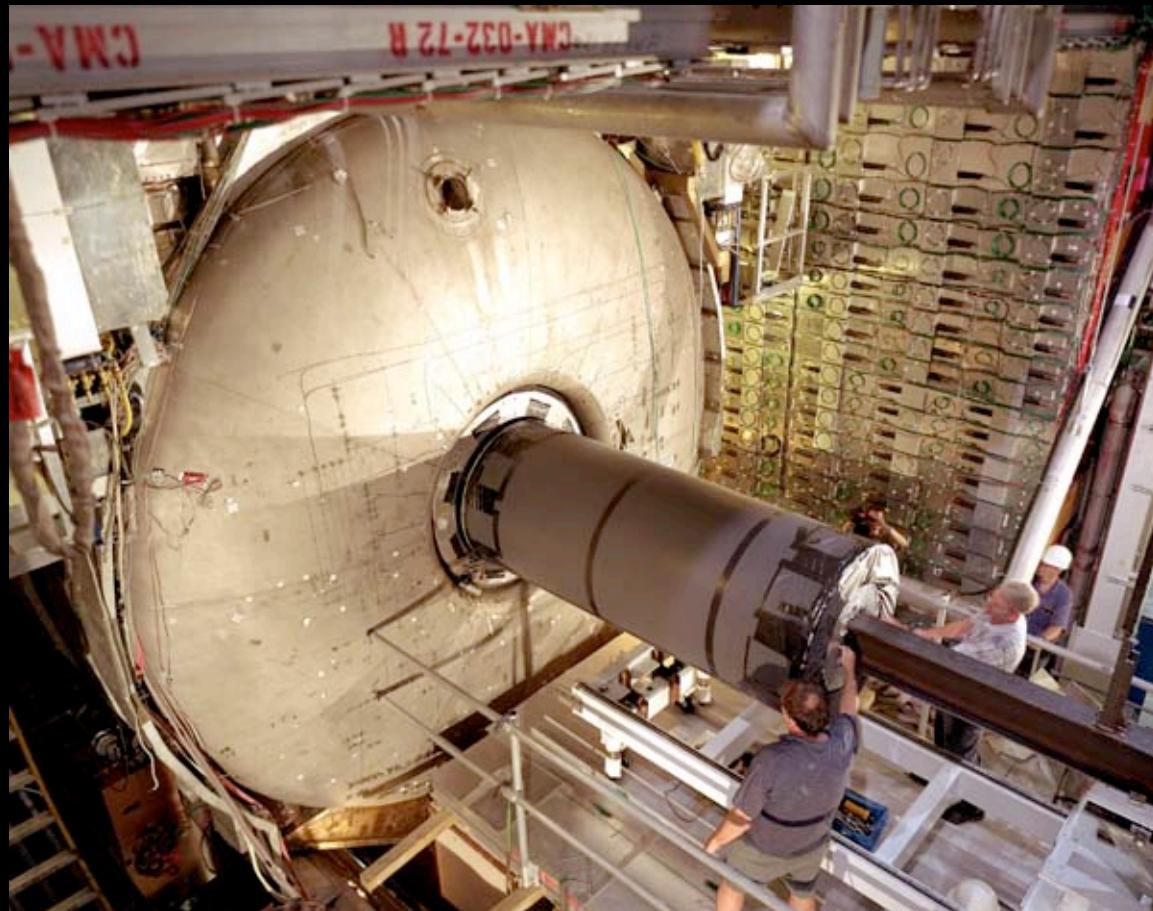
- Began colliding beams in 1983
- Run I (1990-1995)
  - $110 \text{ pb}^{-1}$  / experiment
- Run II (2001- )
  - Will end in 2009-2010
  - $5500 \text{ pb}^{-1}$  / exp so far
  - $\sim 8000 \text{ pb}^{-1}$  / exp total

# Tevatron Experiments: CDF



- 600+ collaborating physicists
  - 63 institutions
  - 15 countries
- 431 publications total
  - 192 in Run II
- I am on CDF

# Tevatron Experiments: D0



- 600+ collaborating physicists
  - 92 institutions
  - 19 countries
- 310 publications total
  - 160 in Run II
- I am not on D0

# Backdrop

- CERN's LHC
  - Proton/Proton Collider at  $E_{cm}=14$  TeV
  - Set to assume WMPC mantle in coming year
  - Home to two Large Experiments (LHCb, Alice)
    - .... and two HUGE Experiments (CMS, Atlas)

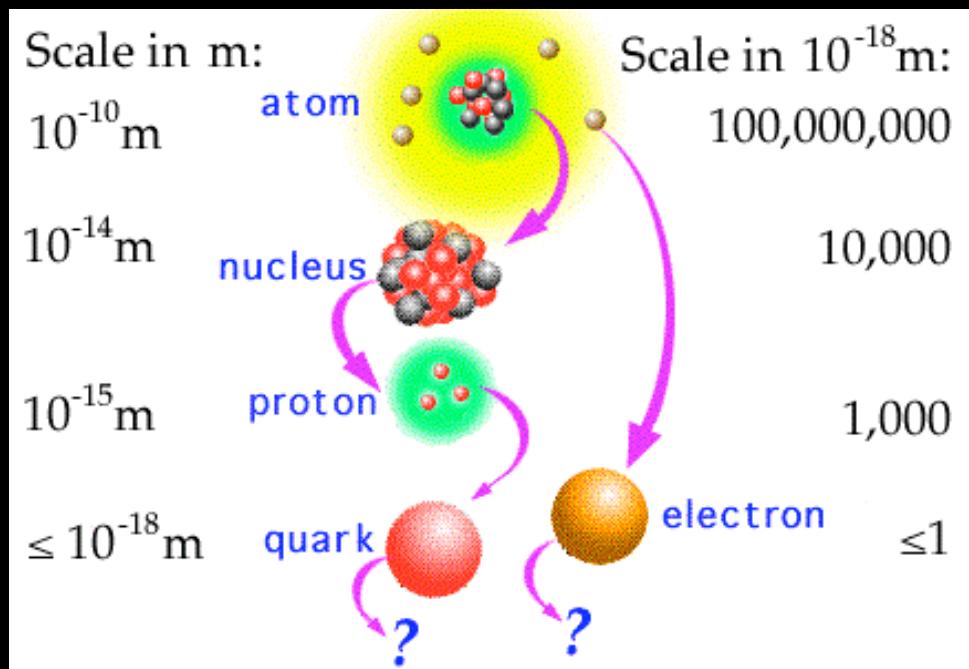
# Outline

- Now seems to me a
  - good time to remind ourselves what HEP aims to accomplish
  - good time recap Tevatron contributions to HEP
  - fun time to speculate about how things will play out

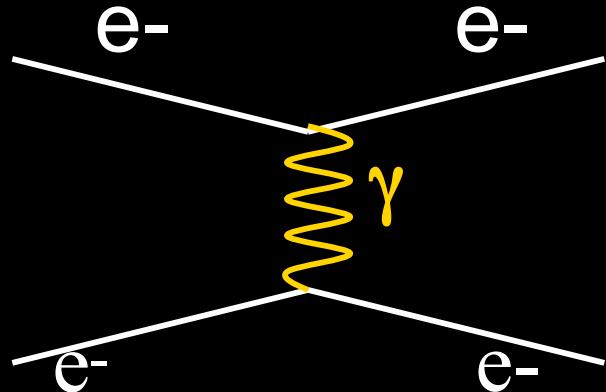
# The Big Picture

## High Energy Physics endeavors to...

1. Identify the elementary particles



2. Understand their interactions



# Our Best Guess: The Standard Model

## 1. The elementary particles...

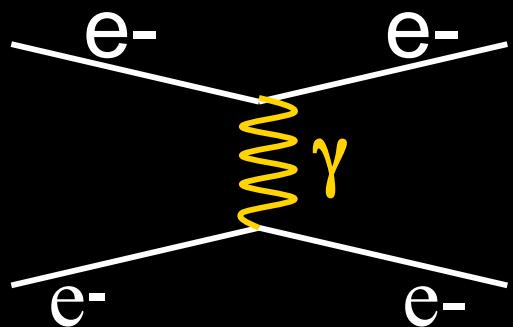
**quarks**  $\begin{pmatrix} u \\ d \end{pmatrix}$   $\begin{pmatrix} c \\ s \end{pmatrix}$   $\begin{pmatrix} t \\ b \end{pmatrix}$  +2/3  
-1/3

**leptons**  $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$   $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$   $\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$  0  
-1

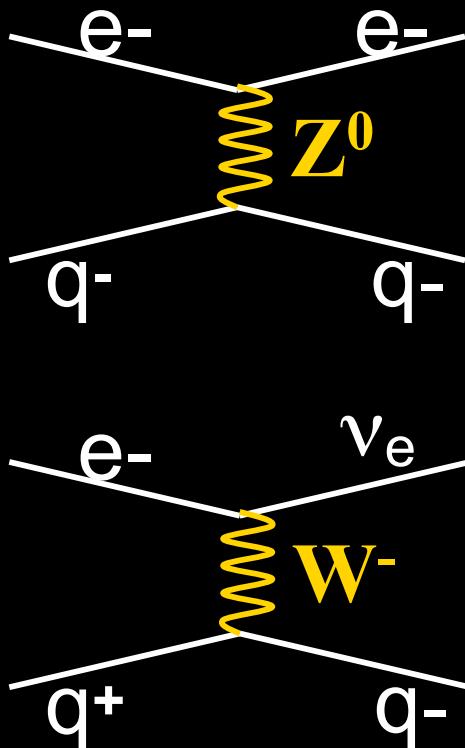
# Our best guess... The Standard Model

## 2. their interactions...

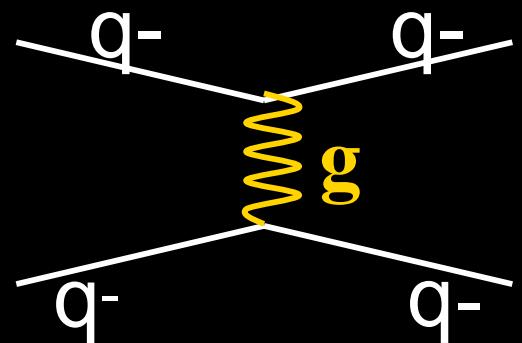
electromagnetic force

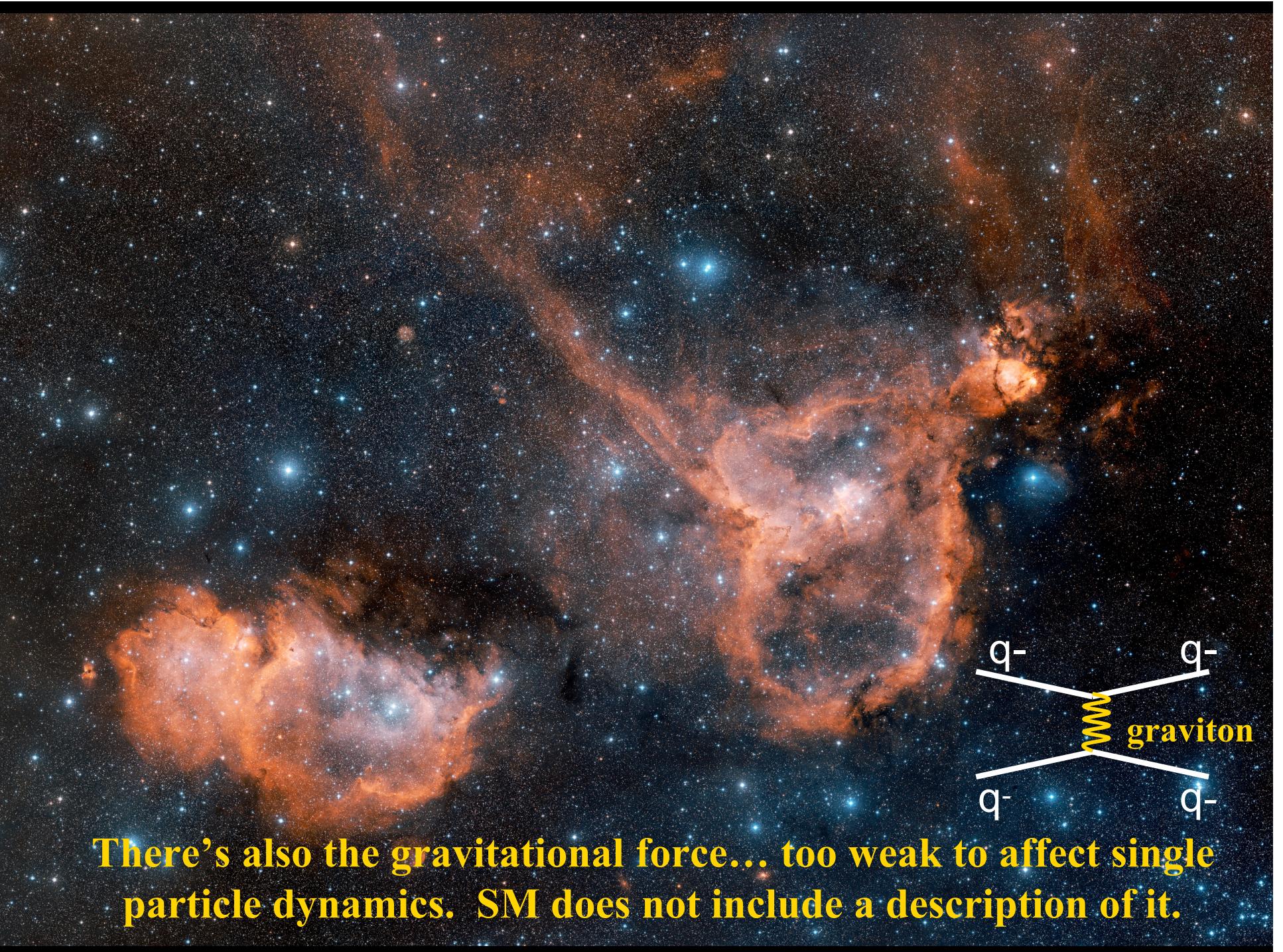


weak force



strong force





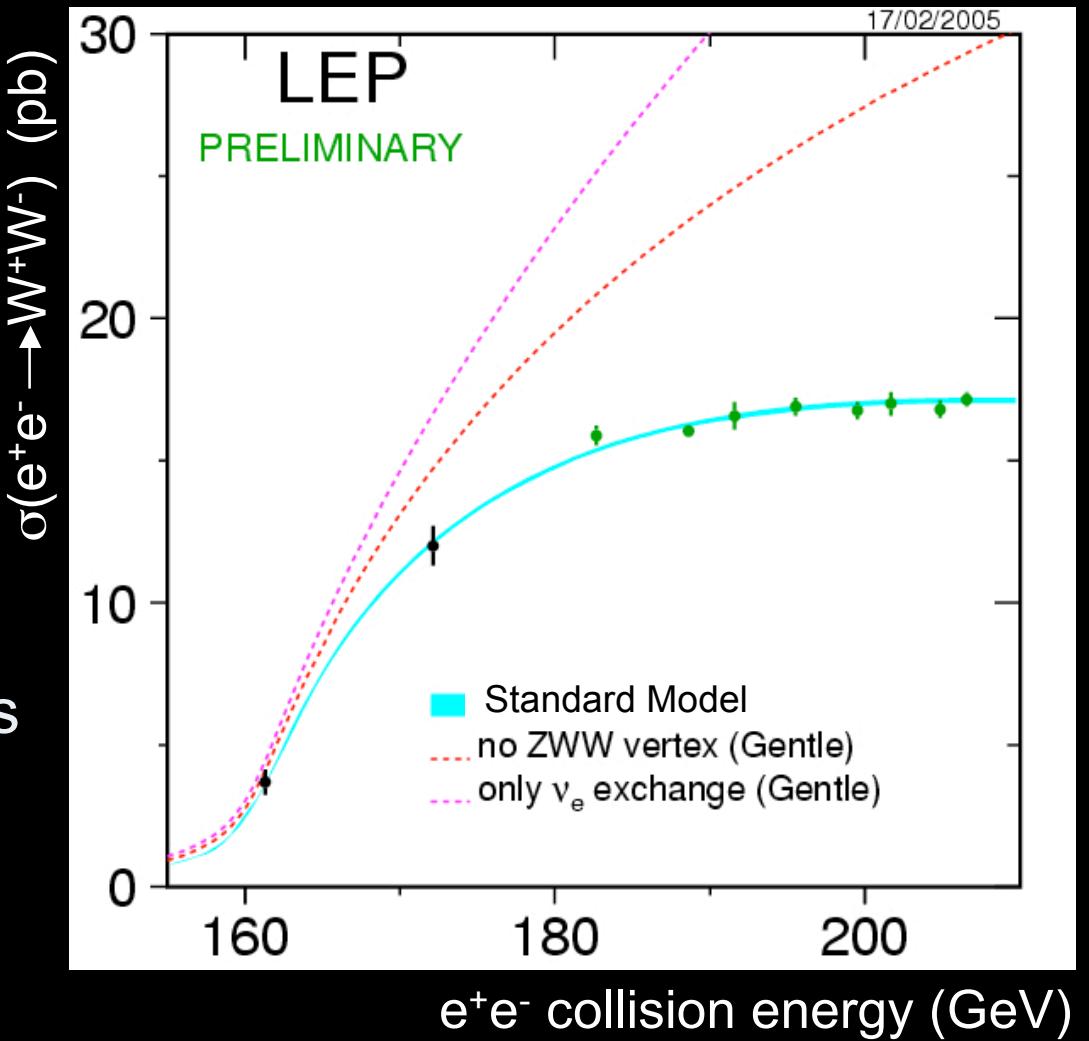
# The Standard Model

- Has been around for several decades
  - Incorporates relativity and quantum mechanics
  - Inherits from Dirac's  $e^+$ , Pauli's  $\nu$ , Fermi...
  - Made theoretically sound by Glashow-Weinberg-Salam (circa 1960)
- Accurately describes all observations... some to great precision
  - Predicted existence of  $W$ ,  $Z$ , several quarks
  - Theory and experiment in agreement over wide range of measurements

# Standard Model Success

Lots of compelling data  
to support particle  
content and gauge  
structure of SM Theory

- discovery of W and Z
- behavior of the couplings  
e.g. the  $e^+e^- \rightarrow WW$  xsec



# Standard Model Success

- have observed all predicted particles

**quarks**  $\begin{pmatrix} u \\ d \end{pmatrix}$   $\begin{pmatrix} c \\ s \end{pmatrix}$   $\begin{pmatrix} t \\ b \end{pmatrix}$

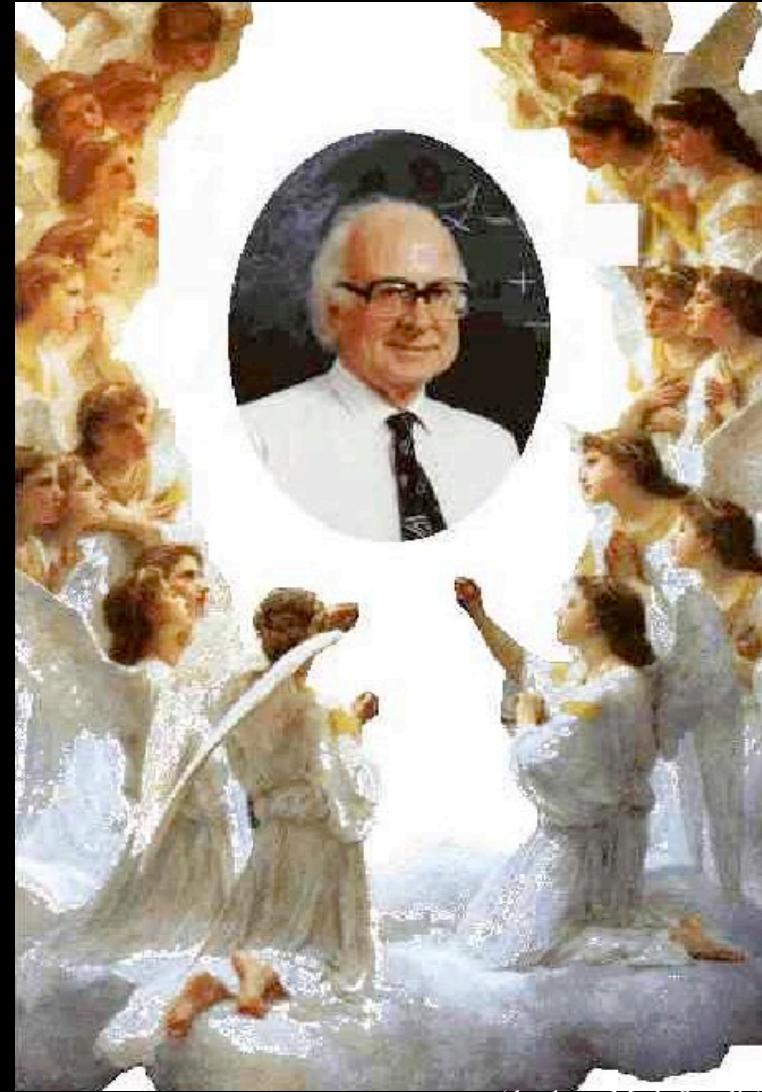
**leptons**  $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$   $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$   $\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$

# Standard Model Success

- have *not* observed any unpredicted particles

# An Important Missing Piece

- **The Higgs Boson**
  - The “God Particle”
  - The “Giver of Heft”
  - The HEP Holy Grail
- unifies EM and Weak forces  
an ElectroWeak Theory
- Higgs is *required* in order  
to generate particle masses
  - W, Z, quarks, leptons



(thanks to Mark Oreglia)

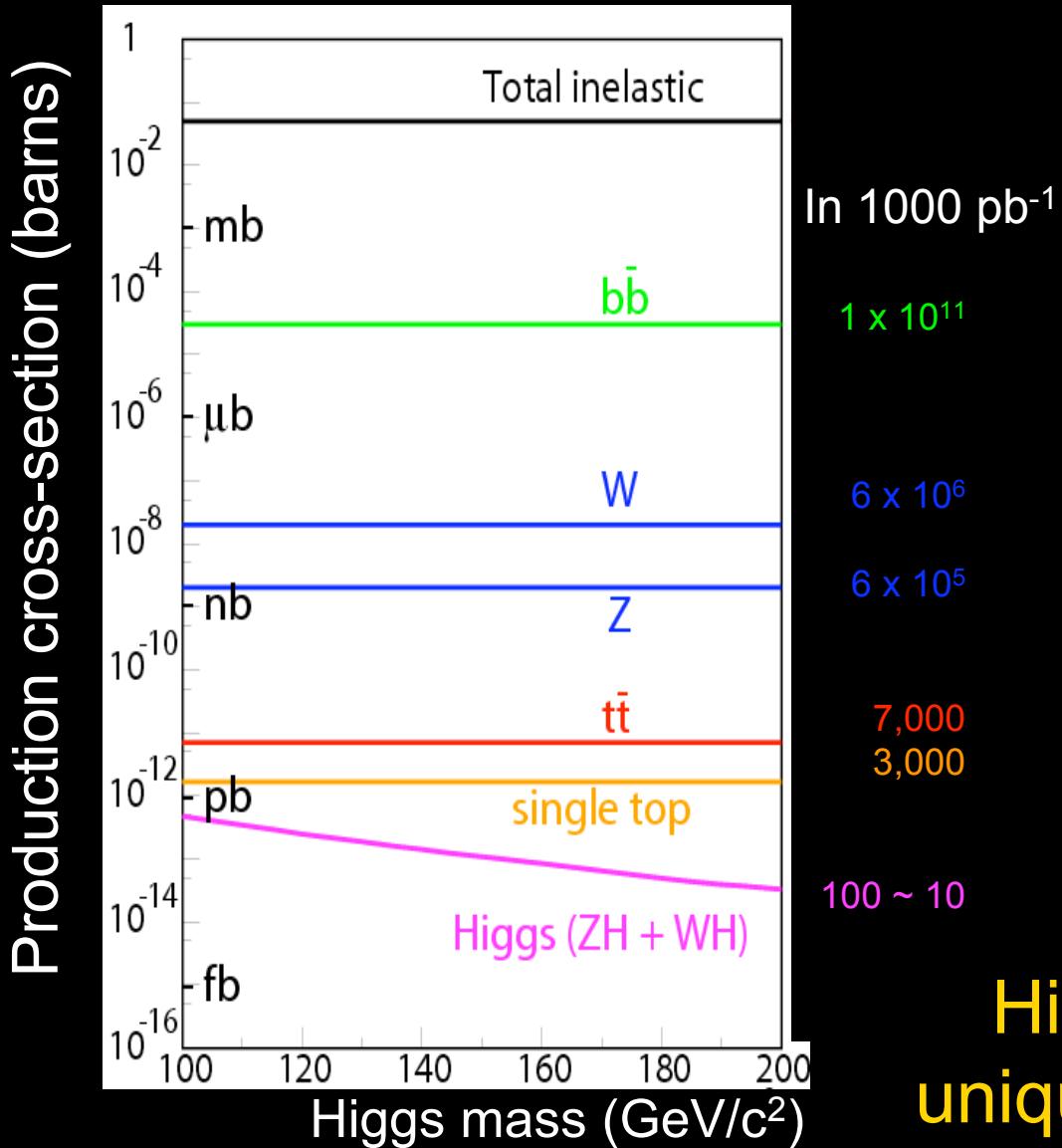
# Beyond the Standard Model

- For all its success, we don't really like the SM
- It has several shortcomings
  - Doesn't include gravity (rather fundamental force)
  - Doesn't unify the forces
  - Fine tuning required
- Several BSM theories which address these shortcomings exist
  - Supersymmetry
  - Extra Dimensions

# HEP Experiment

- **Goal of HEP Experiment:**  
Find out which of these theories are “True”  
(if any)
- **How do we go about doing so?**
  - 1) Test predictions to great precision
  - 2) Continue to look for the Higgs boson
  - 3) Look for BSM particles and interactions
- **Tevatron experiments do all three**

# Tevatron Physics Program



- Strong Force
- B Quarks
- Top Quarks
- Electroweak
- Search for BSM

Highlight a few... those unique to Tevatron program

# An Aside

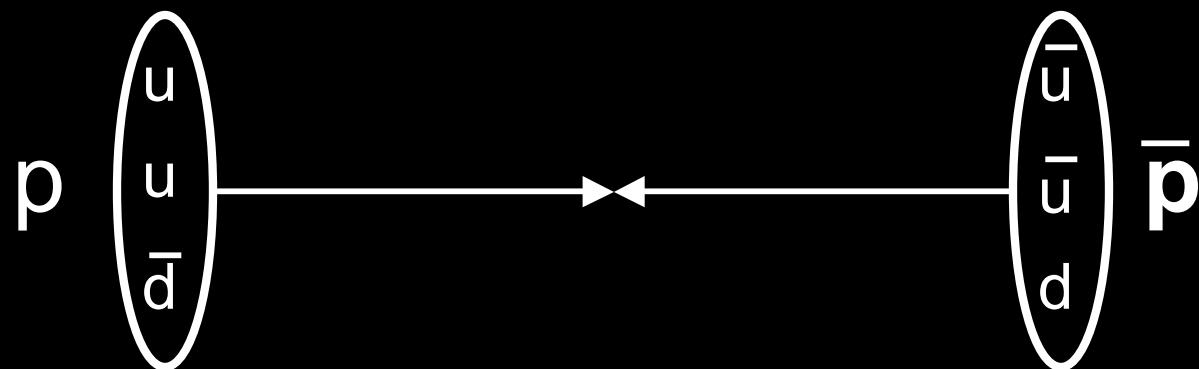
- Some SM Phenomenology with important experimental consequences
  - quarks are only observed in bound states
    - Proton =  $uud$ , Neutron =  $ddu$
    - $\pi^+ = u\bar{d}$ ,  $\pi^- = \bar{u}d$
  - heavy things decay to lighter ones
    - $t \rightarrow b \rightarrow c \rightarrow s \rightarrow u$
    - $\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau$     $W^+ \rightarrow l^+\nu$ ,  $q\bar{q}'$     $Z^0 \rightarrow l^+l^-$ ,  $q\bar{q}$

# An Aside

- The important experimental consequences:
  - Experimentally quarks manifest themselves as streams of stable particles (“jets”)
  - When particles decay, they do so with a characteristic lifetime
  - Only stable (enough) particles traverse the detector volume:  $e$ ,  $\mu$ ,  $\pi$ ,  $K^+$ ,  $p$ ,  $n$ ,  $\gamma$ ,  $\nu$

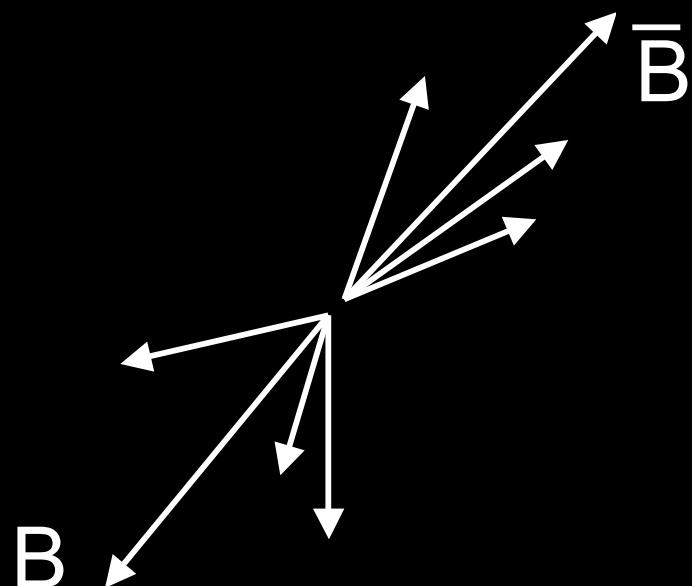
# An Aside

- For example:



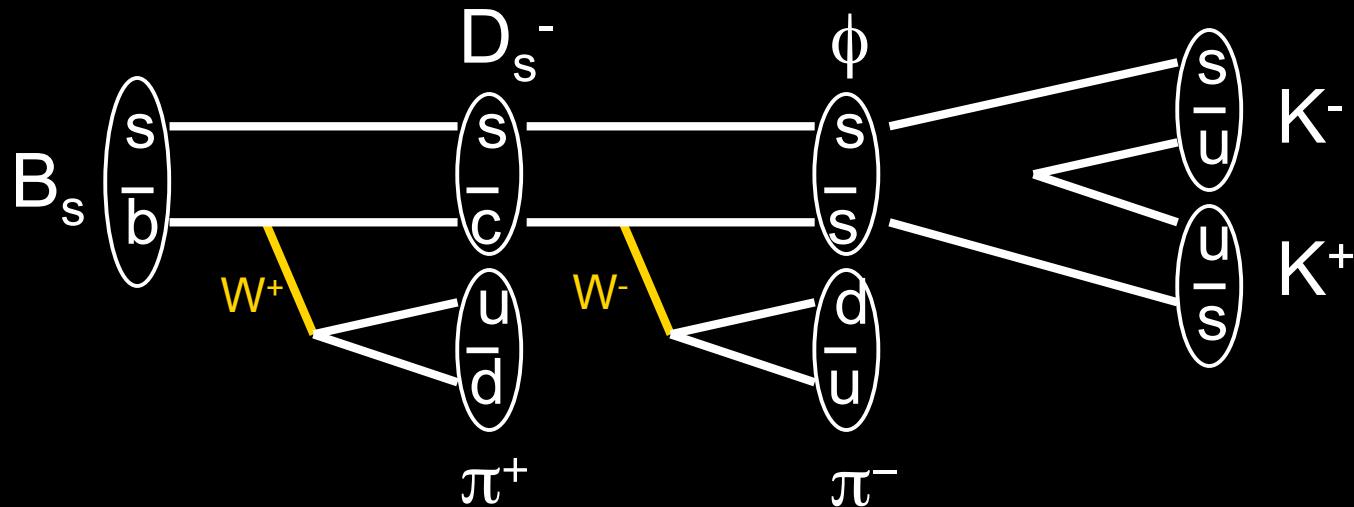
# An Aside

- For example:



# An Aside

- For example:

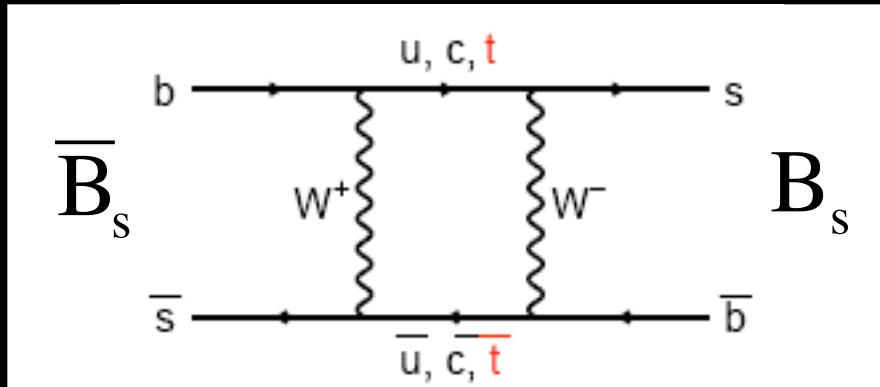


$$B_s \rightarrow D_s^- \pi^+ \rightarrow (\phi \pi^-) \pi^+ \rightarrow ((K^+ K^-) \pi^-) \pi^+$$

# Precision: Determination of $B_s$ Mixing Frequency

# $B_s$ Mixing: What is it?

- $B_s$  particles can change into their anti-particles



- The rate at which  $\bar{B}_s \leftrightarrow B_s$  oscillate:  $\Delta m_s$
- Important check of the Standard Model quark-mixing matrix since  $\Delta m_s \sim V_{ts}$

# $B_s$ Mixing: Why is it important?

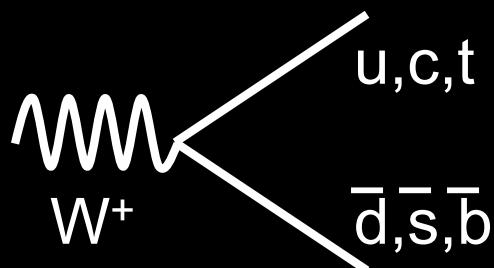
- In our universe today:
  - Matter >> Anti-matter
- ... but when the universe began:
  - Matter = Anti-matter
- The SM quark-mixing matrix offers a mechanism for this to occur
  - Formalized by Cabibbo-Kobayashi-Maskawa (CKM)
  - Verifying this mechanism an important goal of HEP experimental program

# SM Quark-mixing Matrix

- Origin of matter/anti-matter asymmetry is in the ( $\rho - i\eta$ ) terms

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

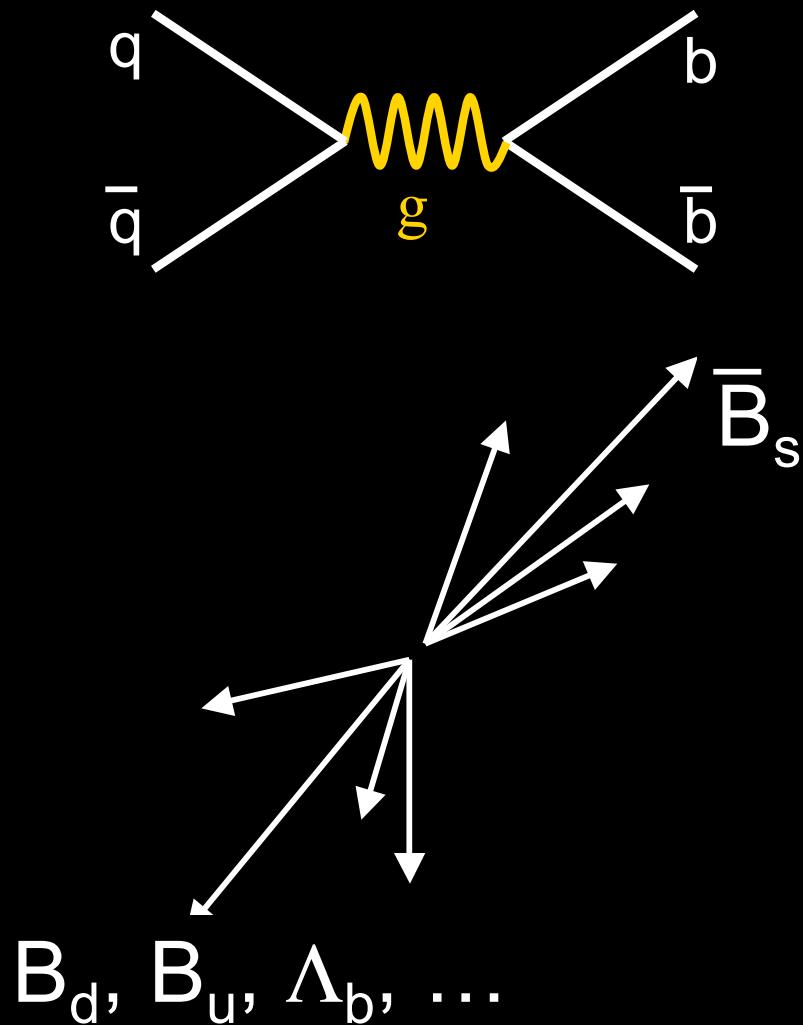
- Size of terms corresponds to strength of  $Wq_1\bar{q}_2$  coupling



$$V_{CKM} = \begin{pmatrix} 0.974 & 0.226 & 0.004 \\ 0.226 & 0.973 & 0.042 \\ 0.009 & 0.041 & 0.999 \end{pmatrix}$$

# $B_s$ Mixing Basics

- Tevatron only place  $B_s$  copiously produced



# B<sub>s</sub> Mixing Basics

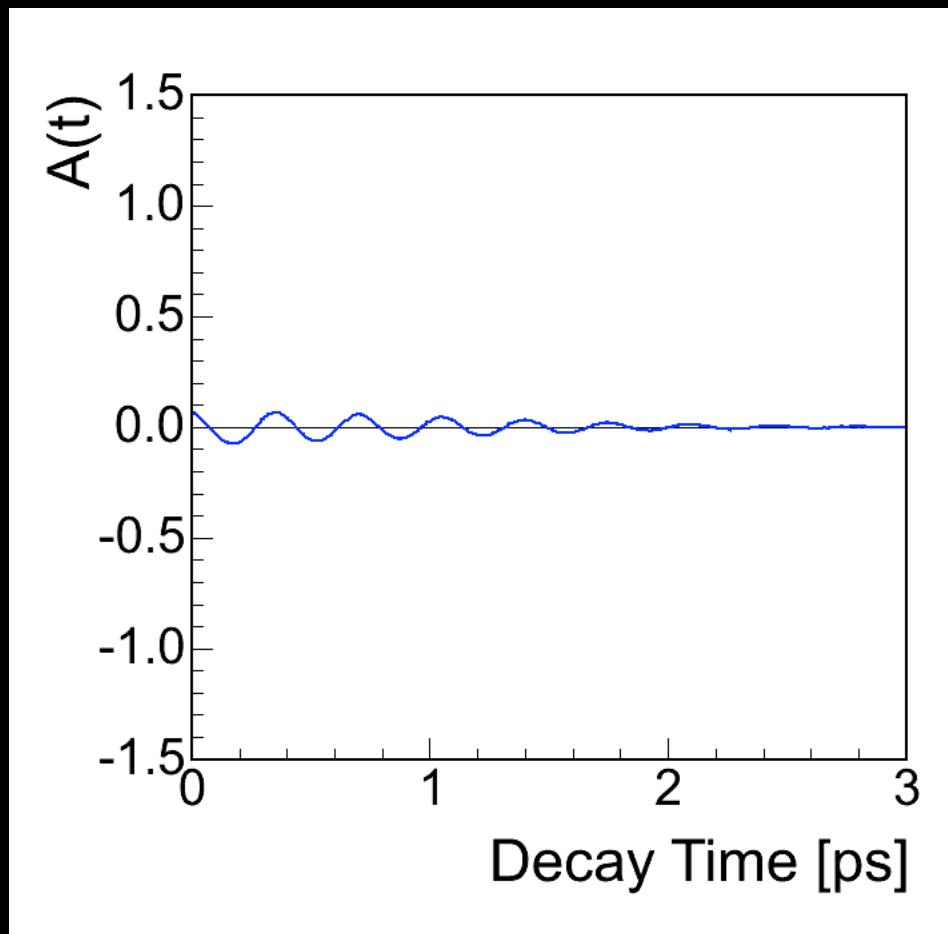
- Probability that B<sub>s</sub> at t=0 decays as  $\bar{B}_s$  at time t

$$P(\text{mixed}) = \frac{1}{2\tau} e^{-\frac{t}{\tau}} (1 - \cos \Delta m_s t)$$

- Experimentally, measure Asymmetry as a function of proper decay time

$$A(t) = \frac{\#\text{unmixed}(t) - \#\text{mixed}(t)}{\#\text{unmixed}(t) + \#\text{mixed}(t)}$$

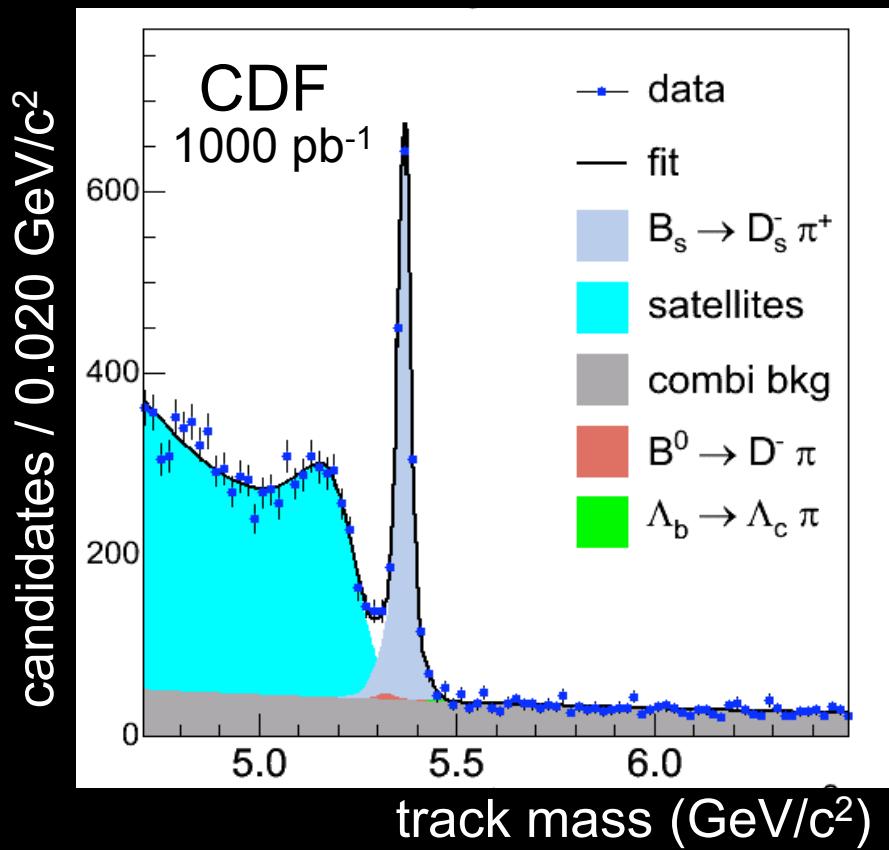
# $B_s$ Mixing: Basics



Actual Detector

# $B_s$ Mixing

- Need to collect as many  $B_s$  particles as possible



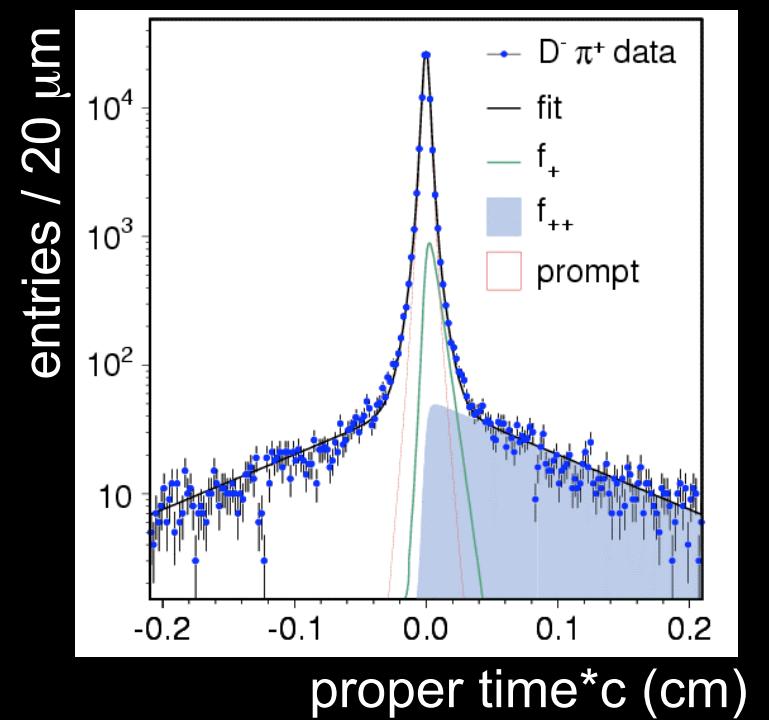
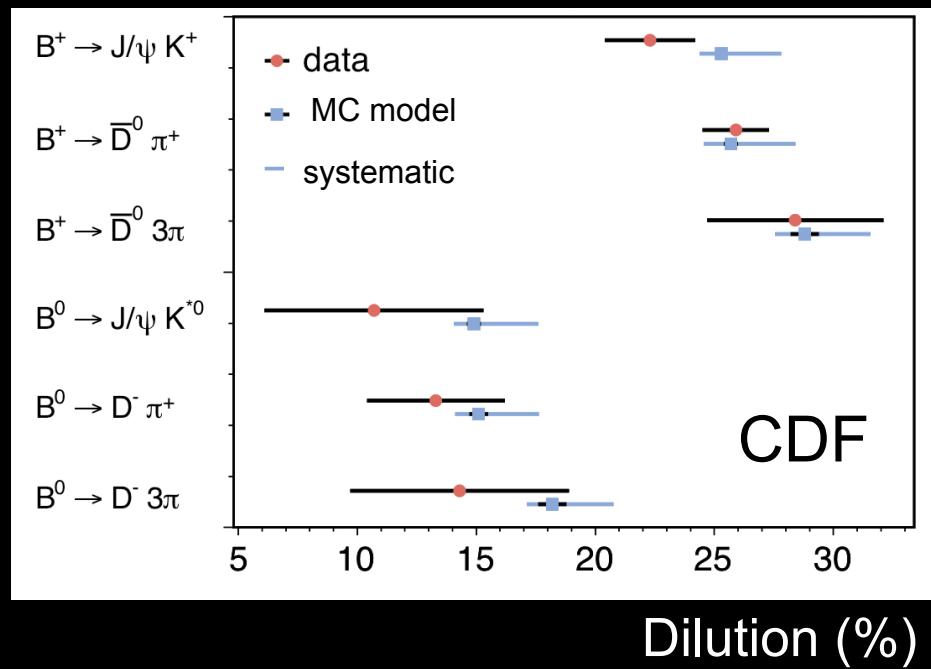
$$B_s \rightarrow D_s^- \pi^+, D_s^- \pi^+ \pi^- \pi^+$$

$$D_s^- \rightarrow \phi \pi^-, K^* K^-, \pi^- \pi^+ \pi^-$$

$$\phi \rightarrow K^+ K^-, K^* \rightarrow K^+ \pi^-$$

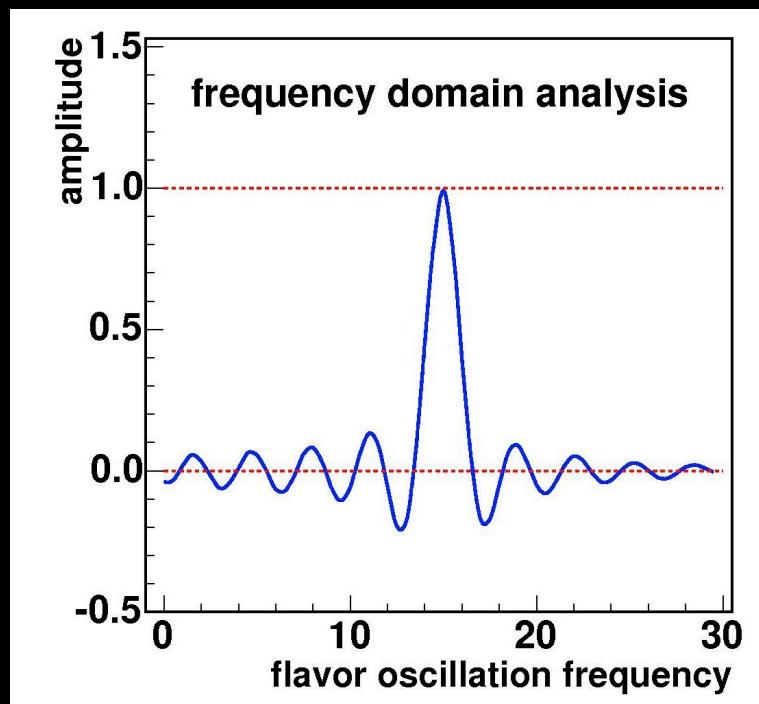
# B<sub>s</sub> Mixing

- Use large control samples to calibrate important detector effects

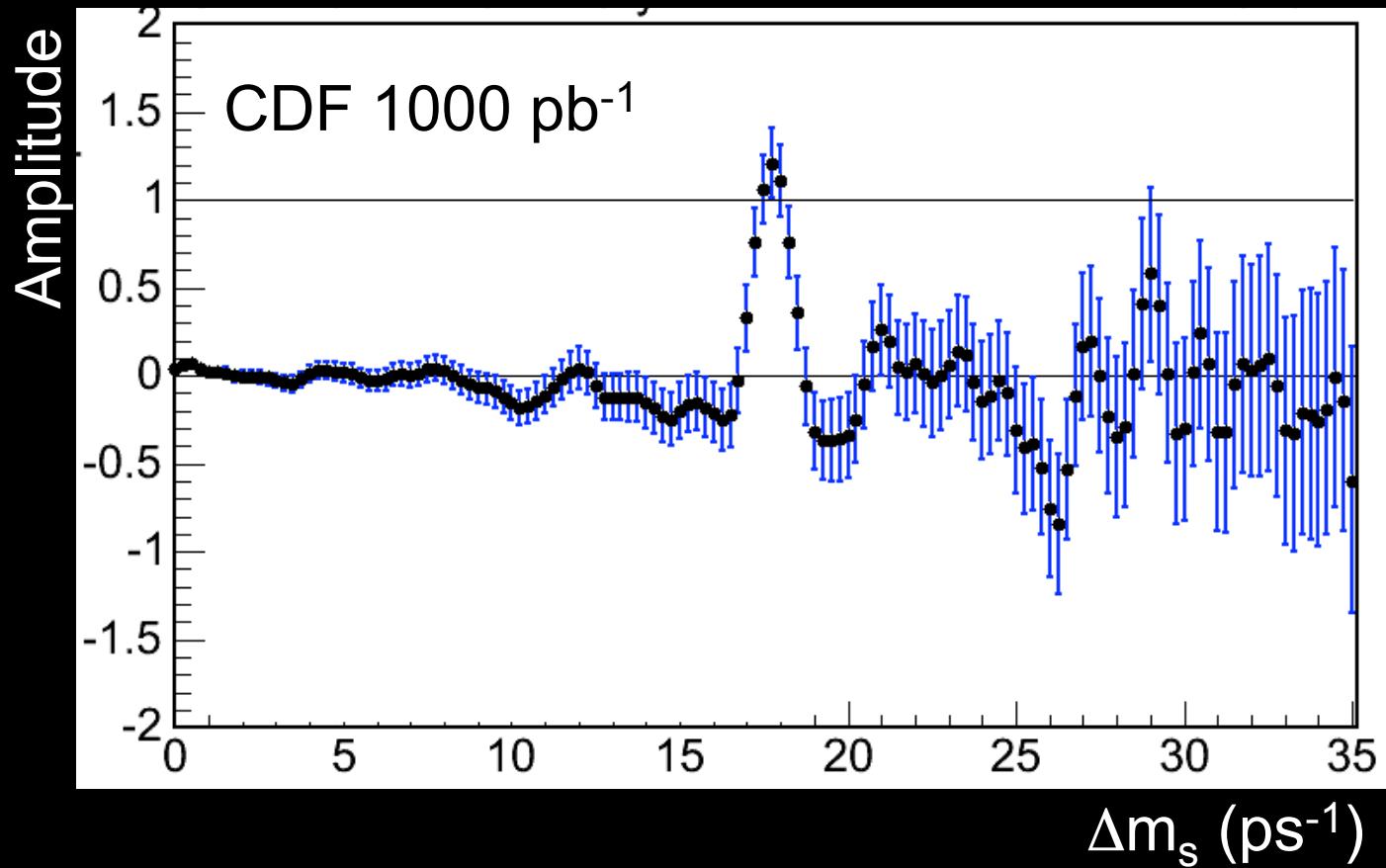


# $B_s$ Mixing Results

- Fourier transform asymmetry distribution
  - Determine amplitude for fixed  $\Delta m_s$
  - Amplitude = 1 at true  $\Delta m_s$ , 0 otherwise

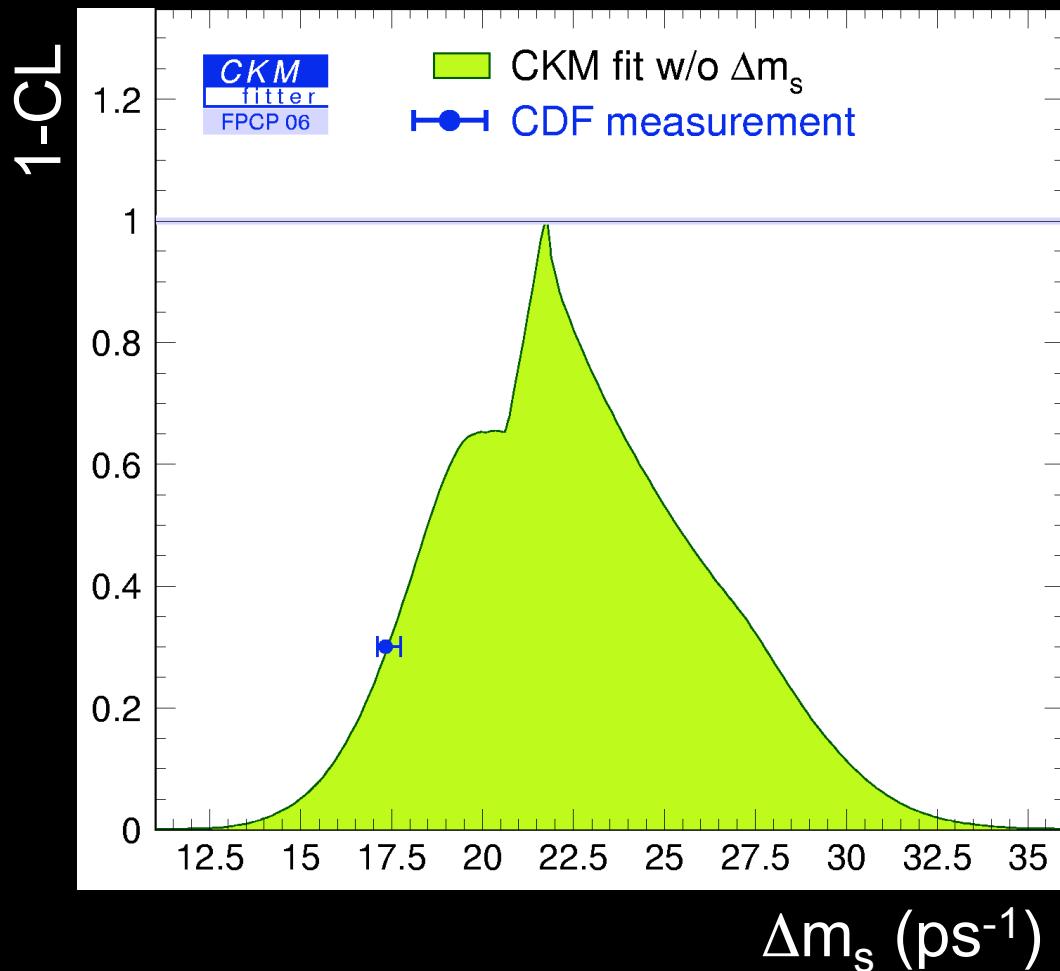


# $B_s$ Mixing Results



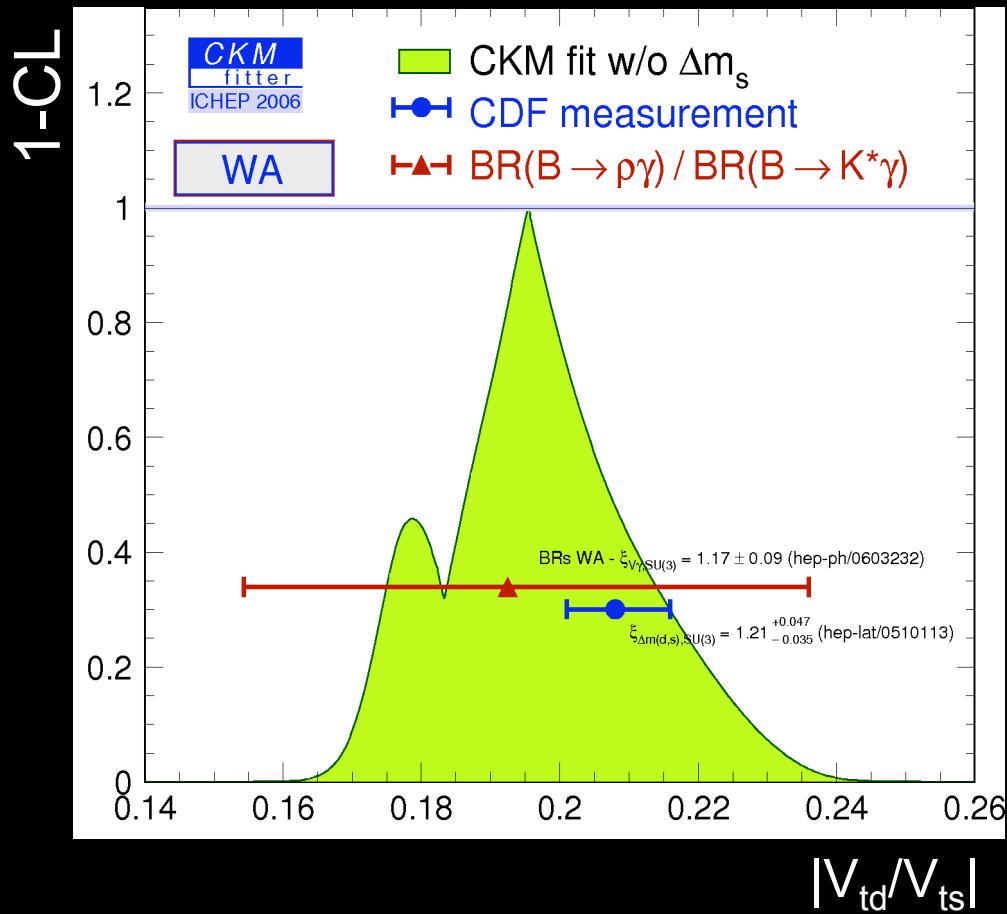
Probability that background could fake this signal  
 $8 \times 10^{-8}$

# $\Delta m_s$ Prediction vs Measurement



- Measurement consistent with SM prediction
- Relative precision  $\delta(\Delta m_s)/\Delta m_s \sim 0.7\%$
- Precision limited by statistics  
 $\delta(\Delta m_s)/\Delta m_s(\text{syst}) \sim 0.4\%$

# B<sub>s</sub> Mixing Constraints



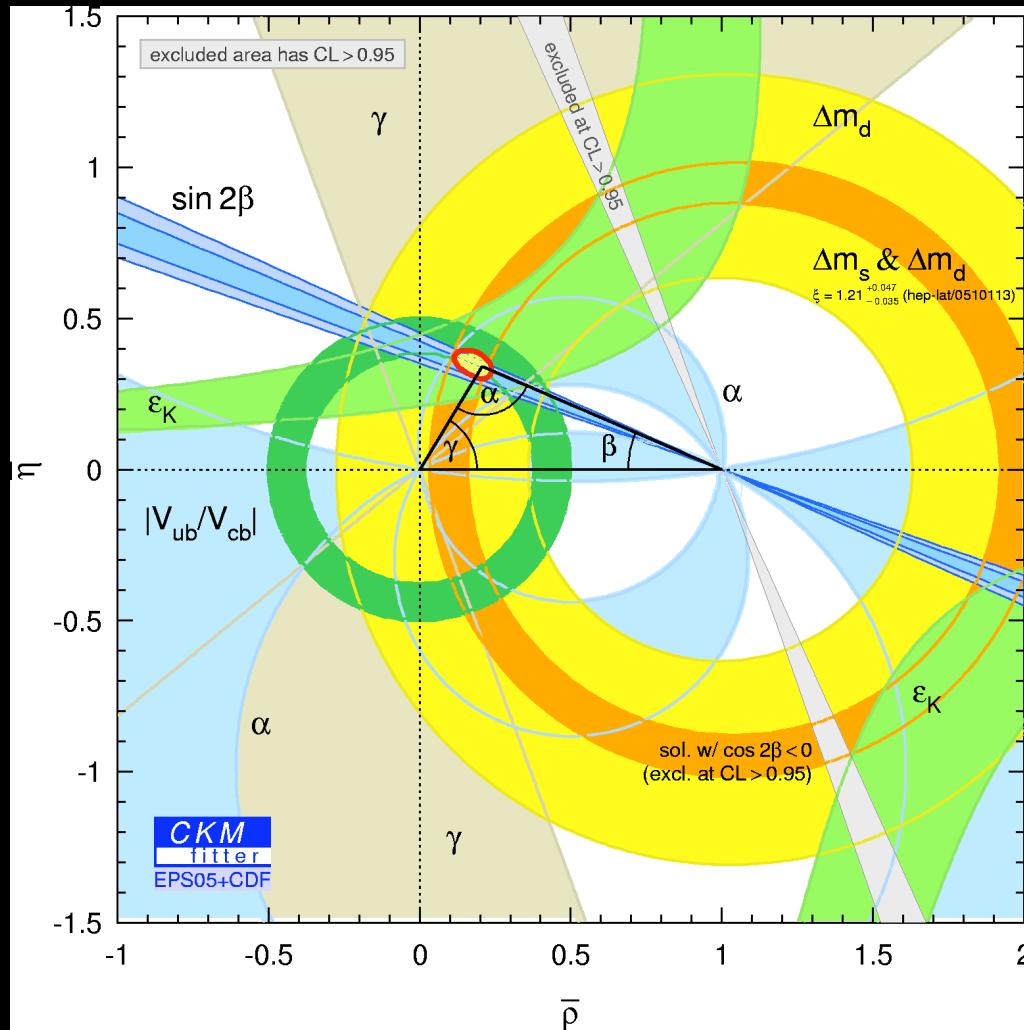
- Constraining CKM matrix

$$\left| \frac{V_{td}}{V_{ts}} \right| = \xi \sqrt{\frac{\Delta m_d}{\Delta m_s} \frac{m_{B_s}}{m_{B_d}}}$$

$$= 0.2060 \pm 0.0007 \text{ (expt)} \quad {}^{+0.0081}_{-0.0060} \text{ (thry)}$$

- 5x more precise than previous determination
- Limited by Lattice calculations

# $B_s$ Mixing Constraints



# Precision: Top Quark and W Boson Mass

# $M_t$ and $M_W$ : Why Important?

- Fundamental prediction of SM:

$$M_W^2 \left( 1 - \frac{M_W^2}{M_Z^2} \right) = \frac{\pi \alpha}{\sqrt{2} G_F}$$

- Measure 3 quantities very very precisely
  - $\alpha$  (electromagnetic coupling constant)
  - $G_F$  (Fermi constant)
  - $M_Z$  (mass of the Z boson)
- Predict 4th and compare to measurements
  - $M_W$  (mass of the W boson)

# $M_t$ and $M_W$ : Why Important?

- Actually, not quite that easy...

$$M_W^2 \left( 1 - \frac{M_W^2}{M_Z^2} \right) = \frac{\pi \alpha}{\sqrt{2} G_F} (1 + \Delta r)$$

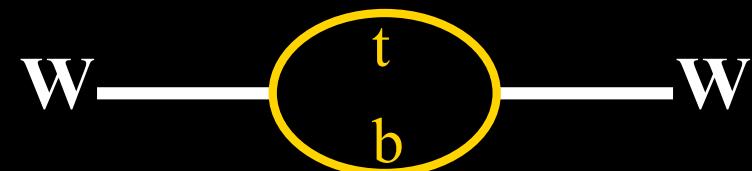
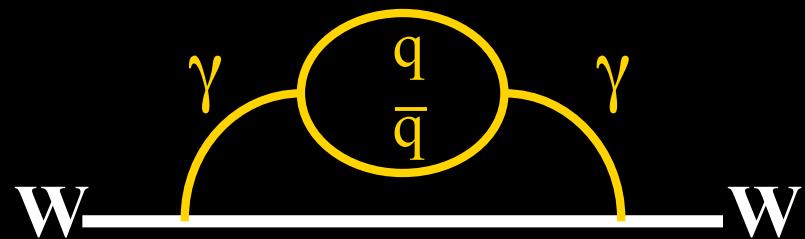
where,

$$\Delta r = \Delta \alpha(\Pi^{\gamma\gamma}) + \Delta \rho(M_t^2) + \Delta r_{rem}(\ln(M_t^2), \ln(M_H^2))$$

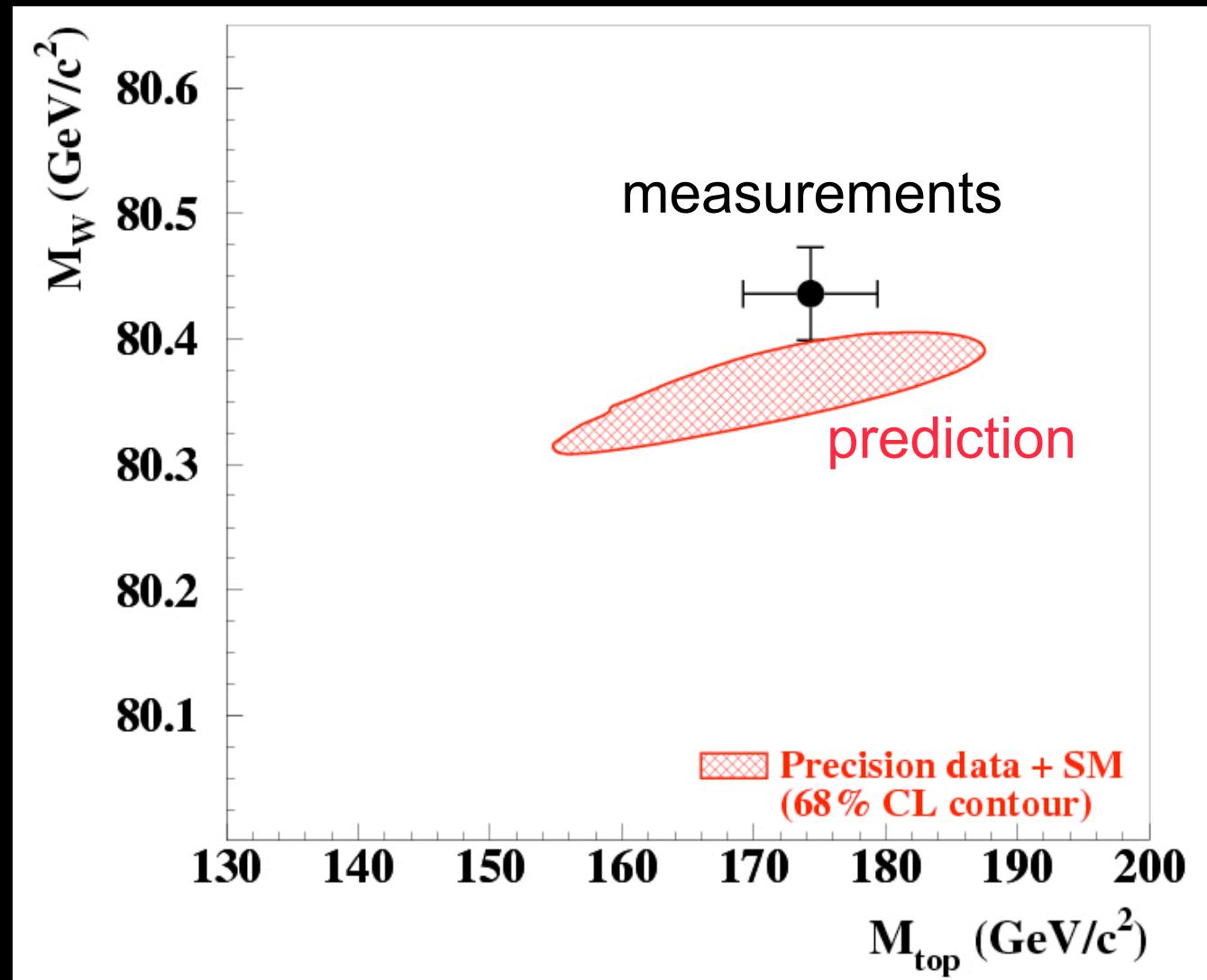
- So we can use precision data + SM to predict experimental observables (e.g.  $M_W$ )
  - Test SM predictions
  - Constrain mass of the SM Higgs boson

# Radiative Corrections in 3000 words

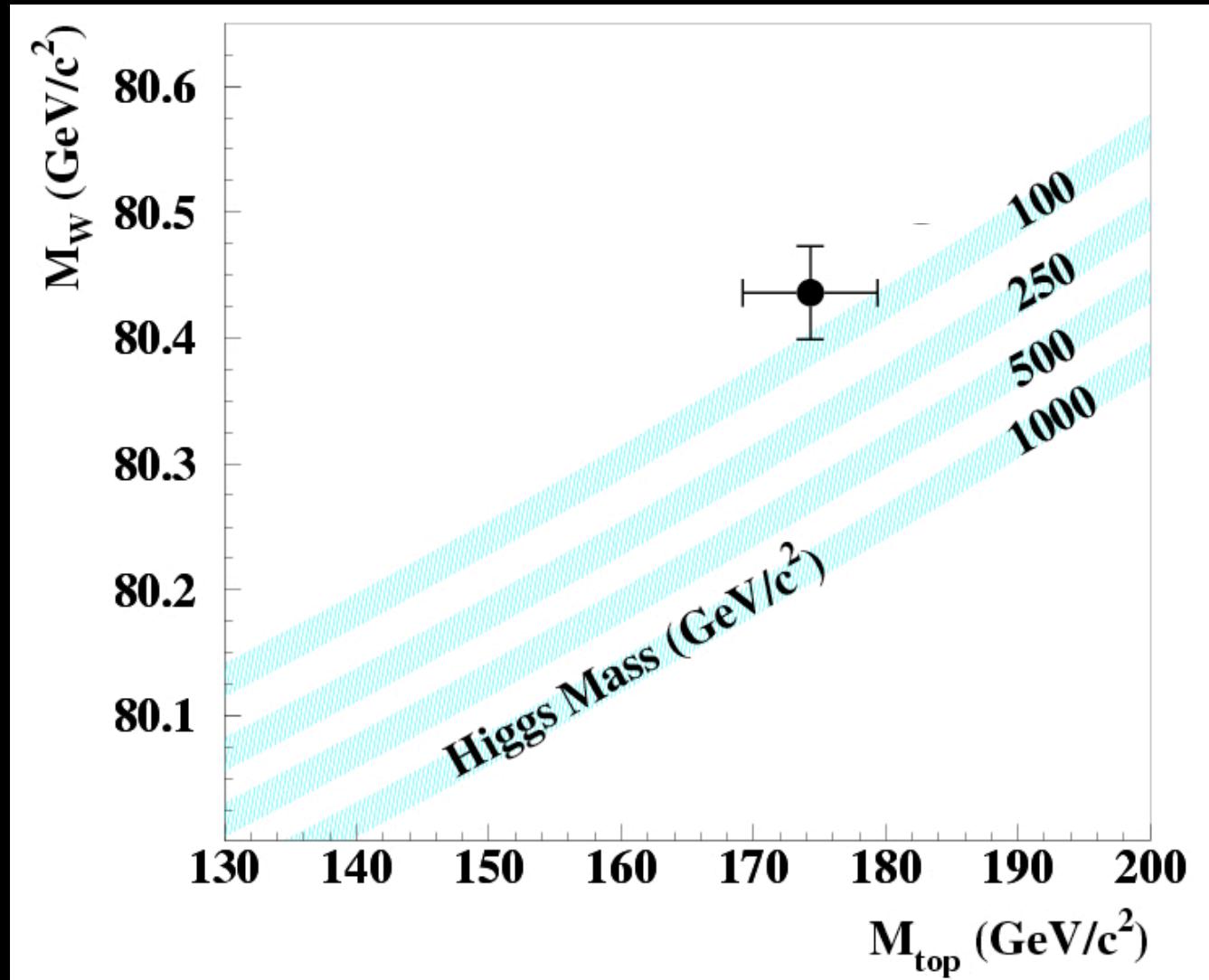
$$\Delta r = \Delta\alpha(\Pi^{\gamma\gamma}) + \Delta\rho(M_t^2) + \Delta r_{rem}(\ln(M_t^2), \ln(M_H^2))$$



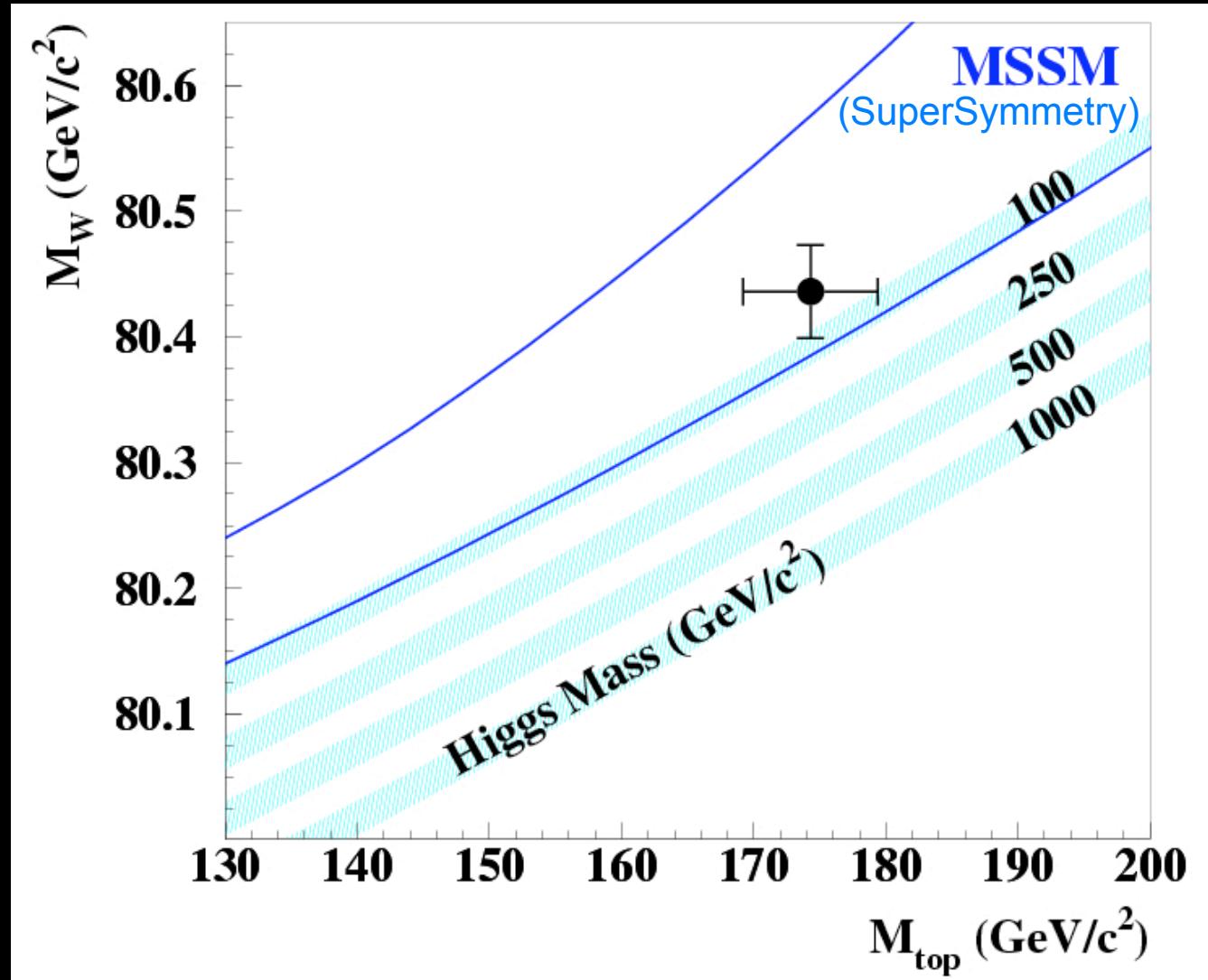
# Using $M_t$ and $M_W$ to test SM



# Using $M_t$ and $M_W$ to Constrain $M_H$

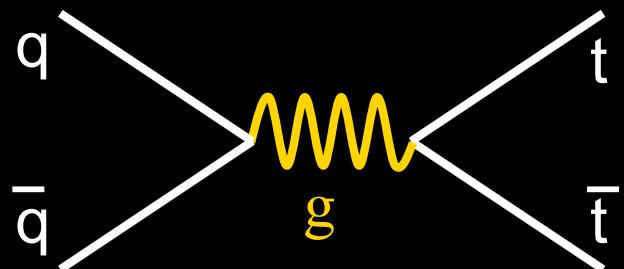


# Using $M_t$ and $M_W$ to Probe BSM



# Measuring $M_t$

- Tevatron only place in the world producing top quarks



- Predominantly produced in pairs via the strong interaction

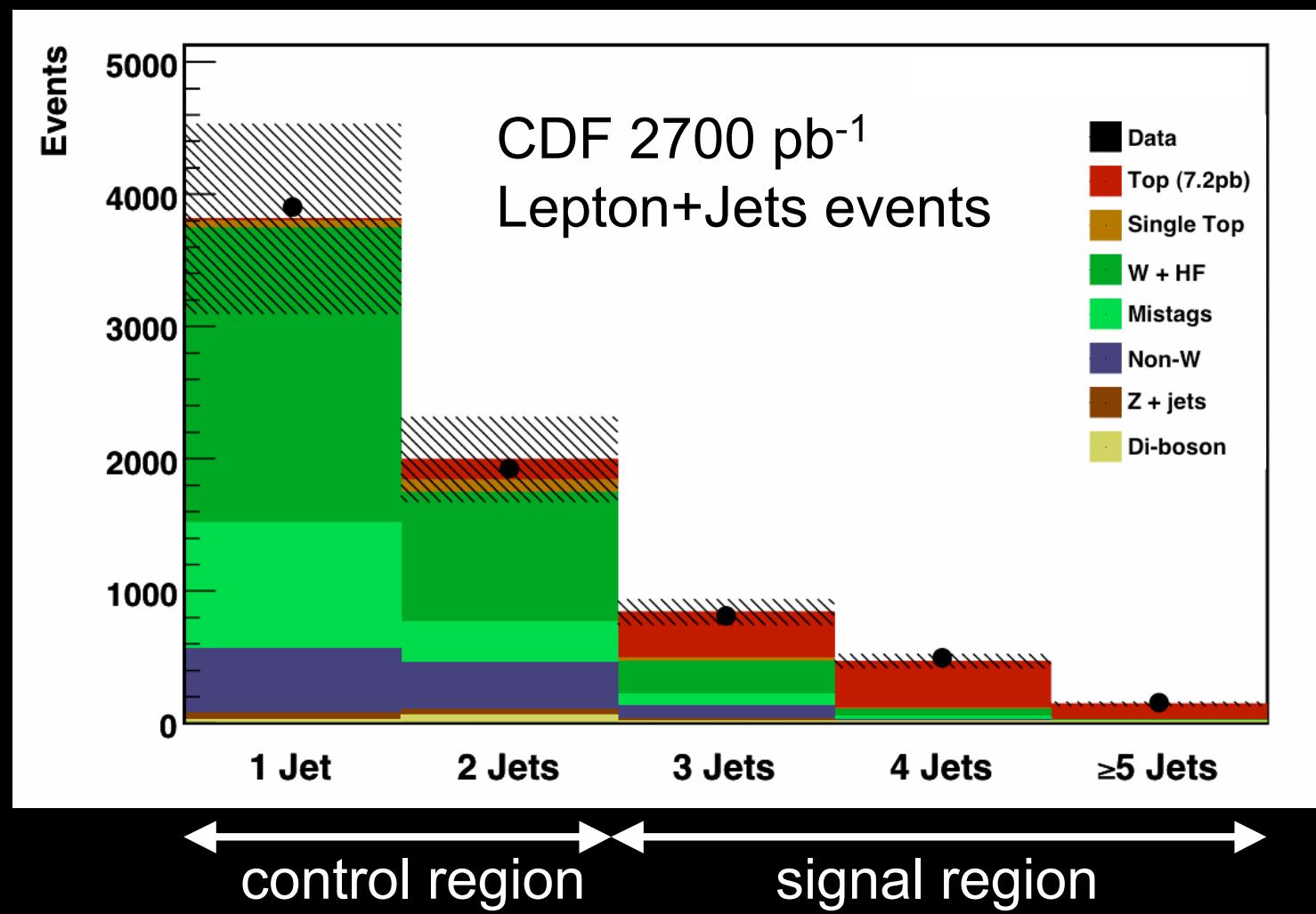
# Measuring $M_t$

- Since  $M_t > M_W + M_b$  and  $V_{tb} \gg V_{ts}, V_{td}$ 
  - Top quark decays before it hadronizes  
(ie. can measure properties of bare quark)
  - Top quark decays to a W-boson+b-quark
- Final state determined by W decays

$$t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow q\bar{q}' q\bar{q}' b\bar{b}$$

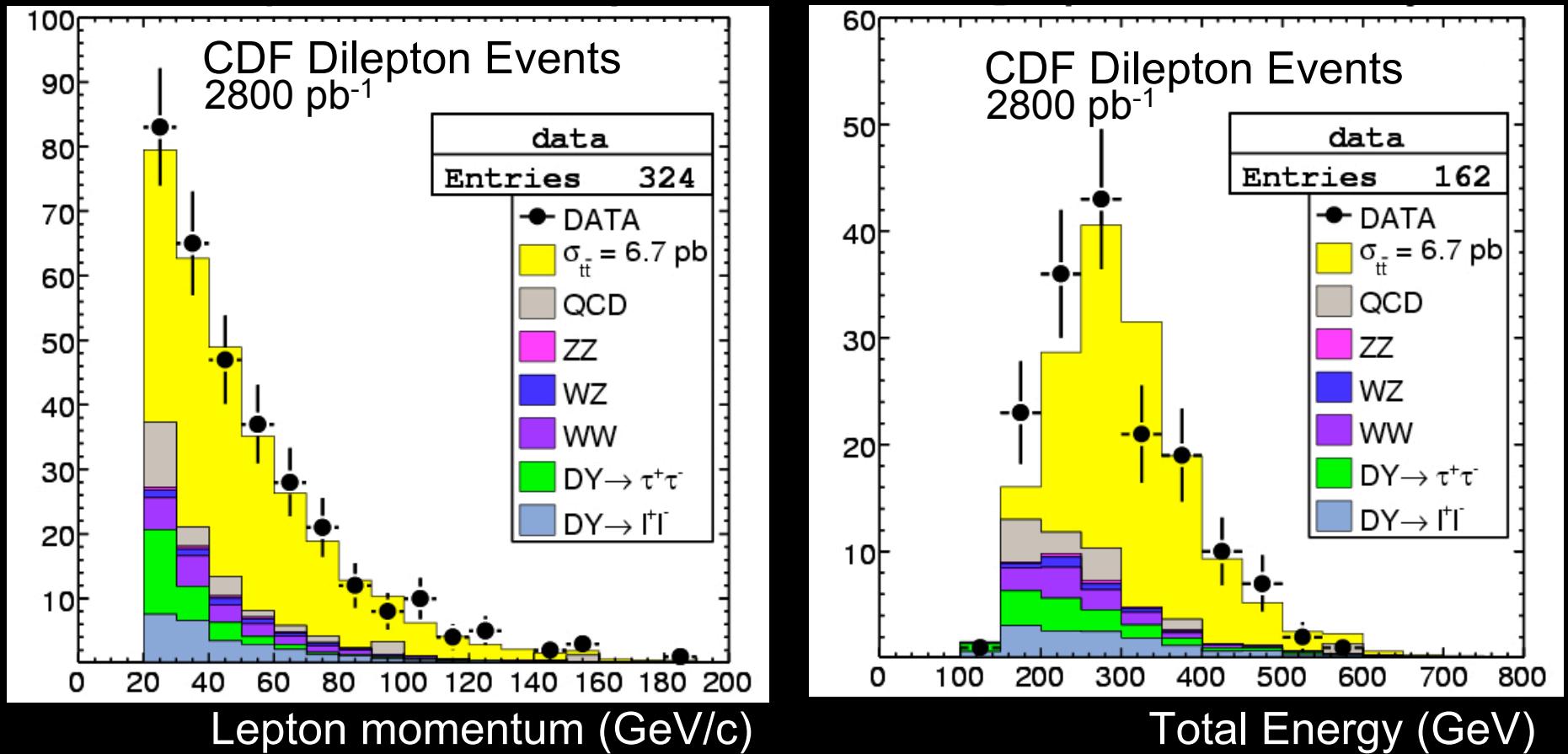
“All Jets”

# Measuring $M_t$



- Sample composition well understood

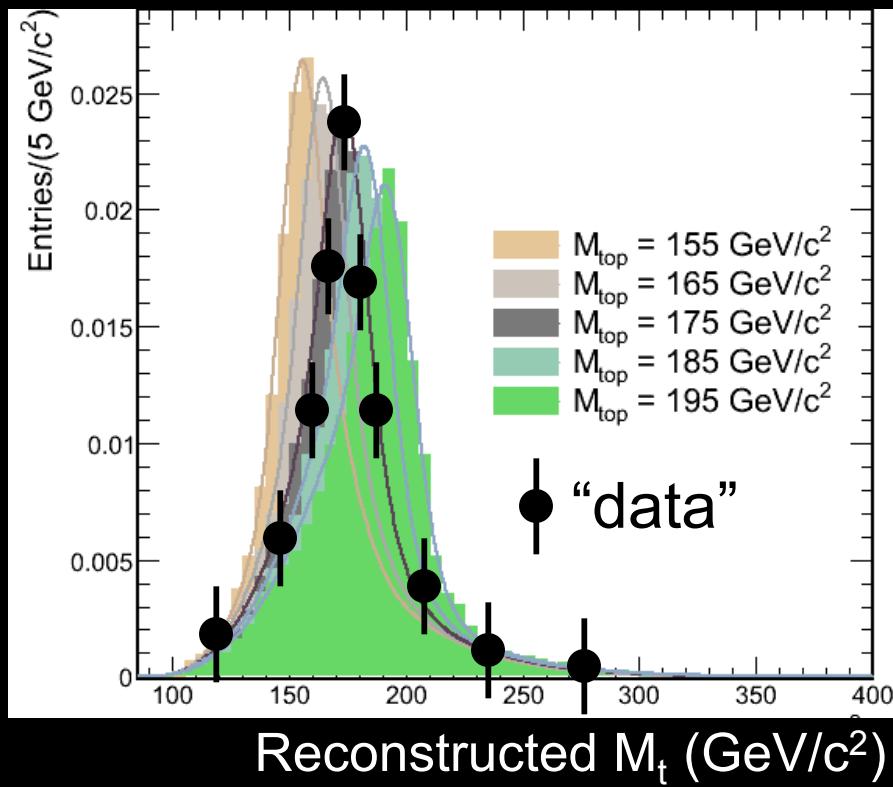
# Measuring $M_t$



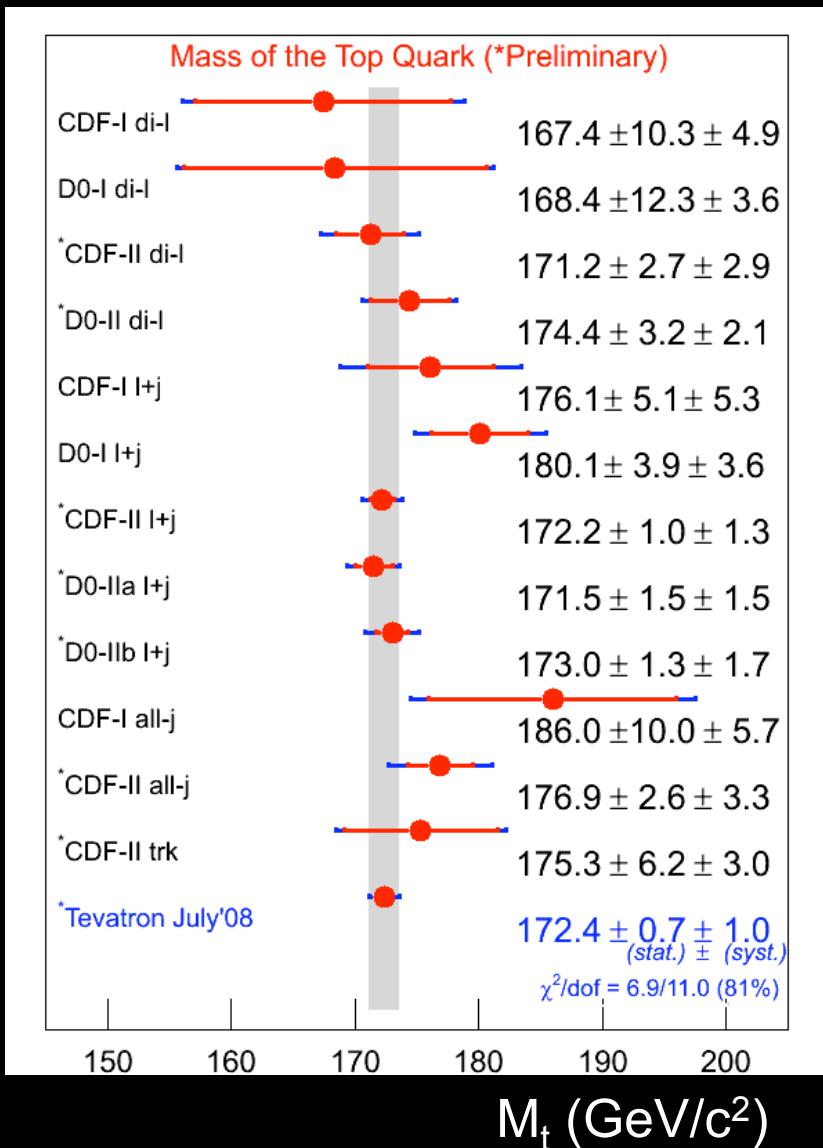
- Kinematics well modeled

# Measuring $M_t$

- Final  $M_t$  determined by comparing data to predictions generated assuming various  $M_t$



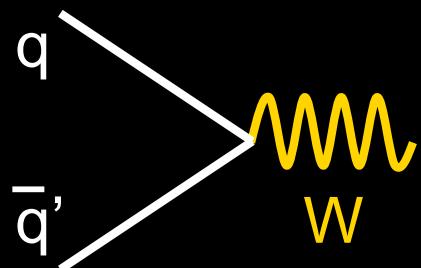
# M<sub>t</sub> Results



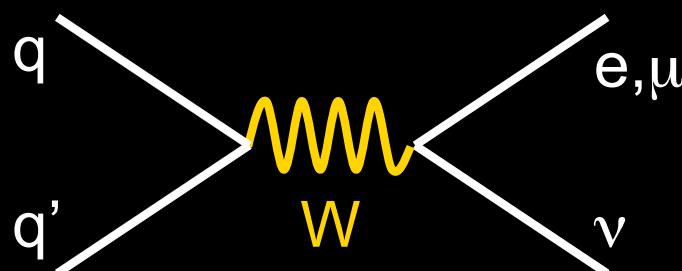
- Consistent across all final states
- In combination  $\delta M/M=0.7\%$
- 2x better than originally projected
  - Thanks to analysis improvements
  - Can get better

# Measuring $M_W$

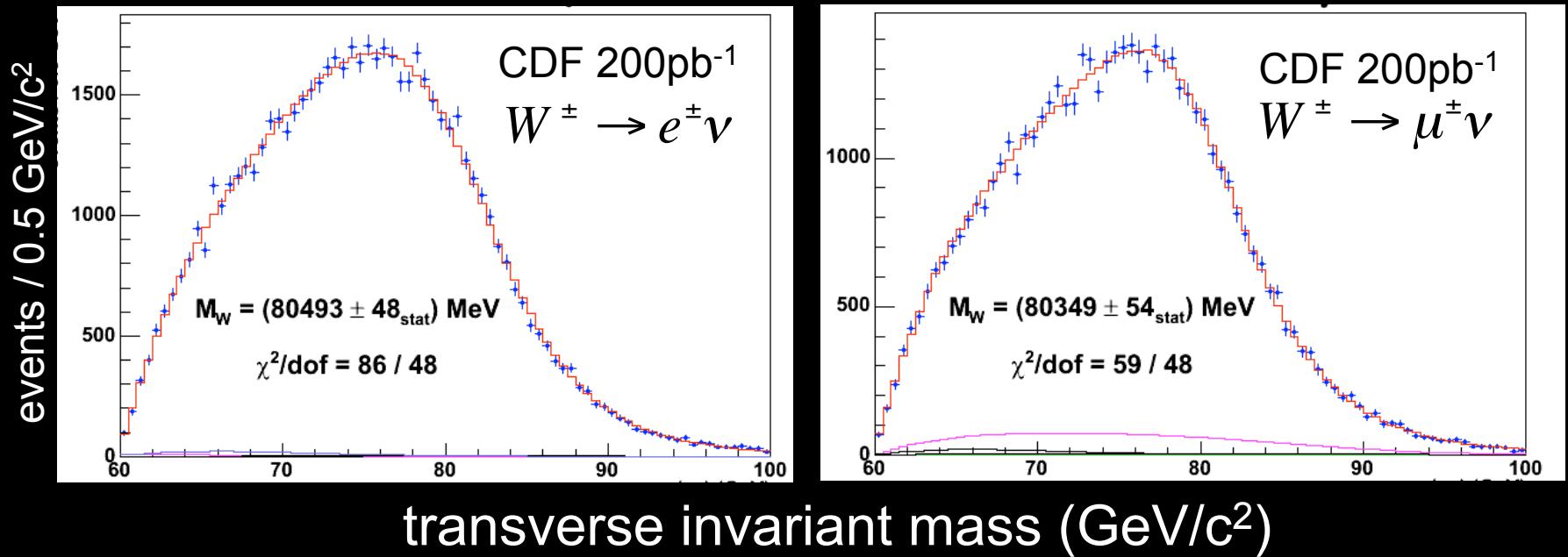
- Tevatron a W-boson factory



- Experimentally it's easiest/best for us to use the leptonic decays

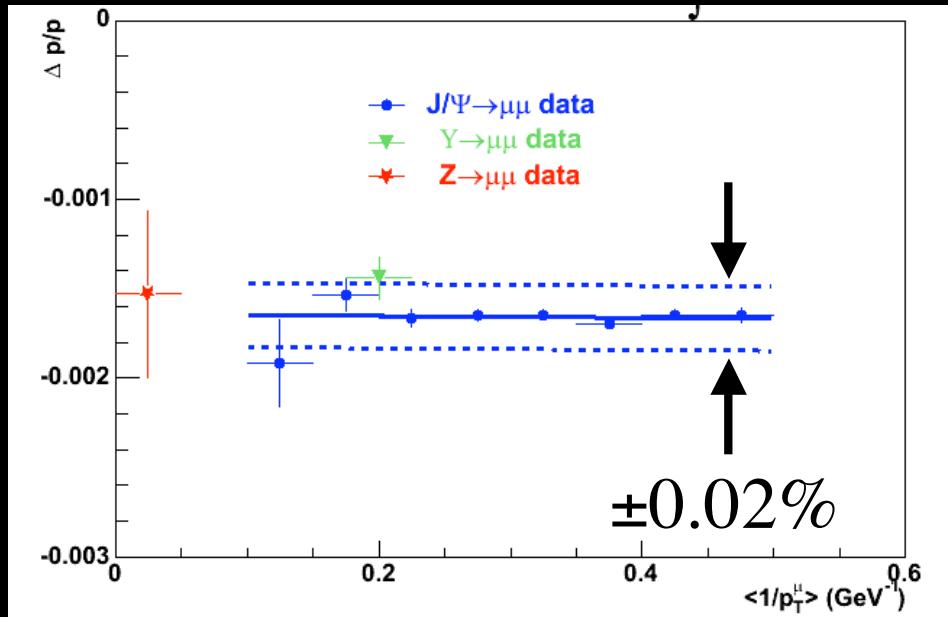
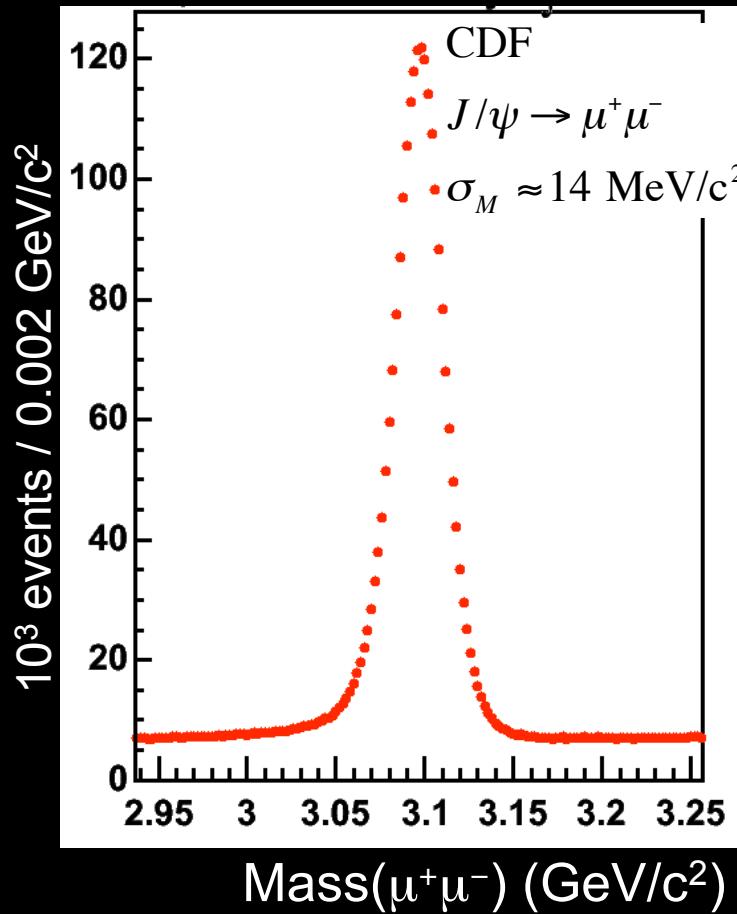


# Measuring $M_W$



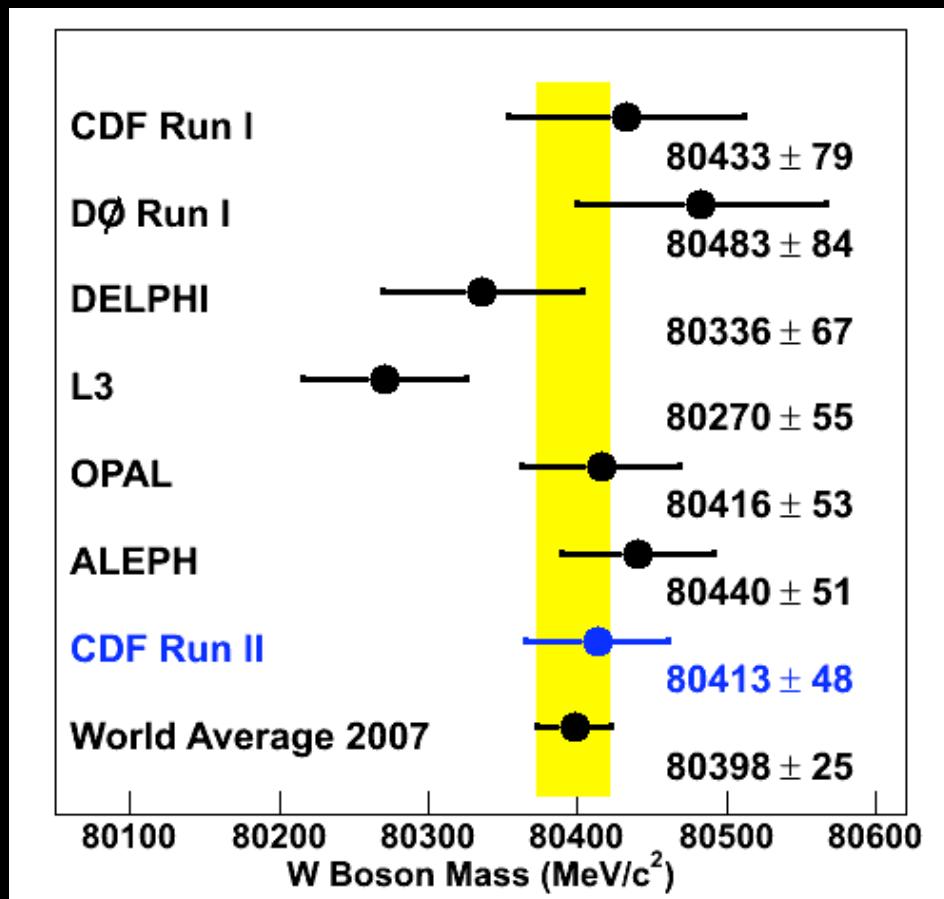
- We collect  $O(10^5)$   $W$  bosons with high purity

# Measuring $M_W$



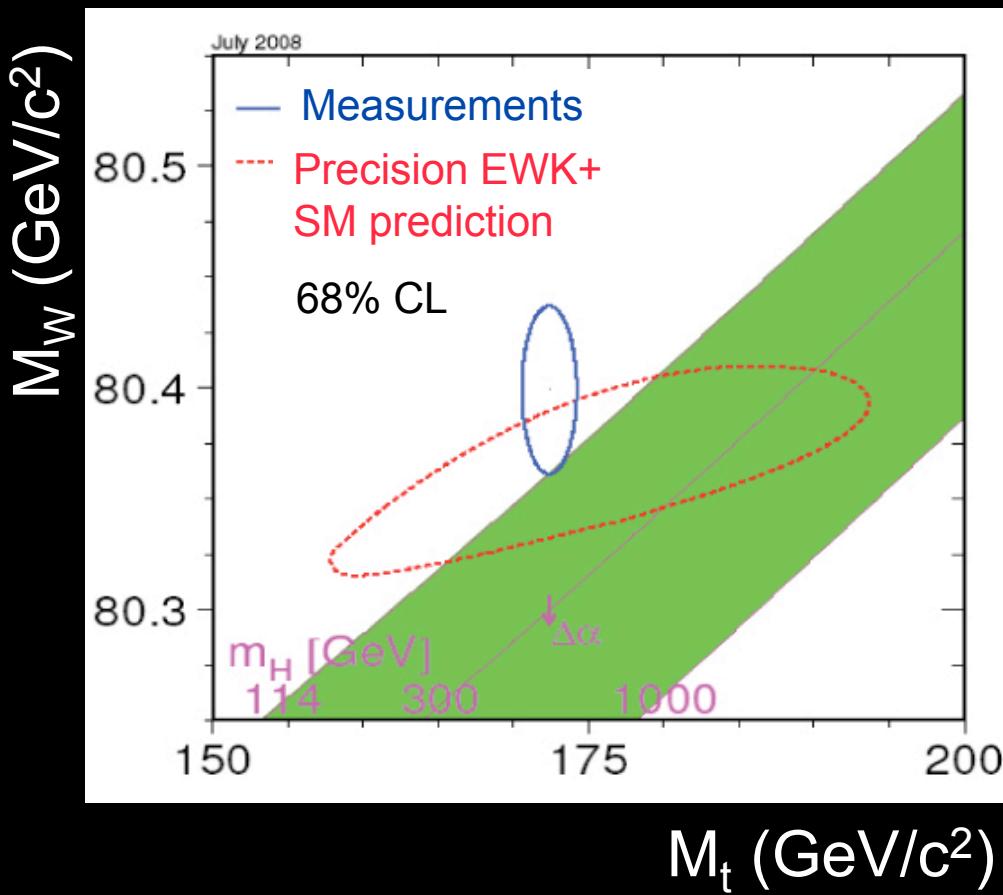
- We collect calibration samples with millions of events

# $M_W$ Results



- Using  $200 \text{ pb}^{-1}$  have world's best  $\delta M_W/M_W = 0.06\%$
- Will get better
  - Largest syst are stat dominated
  - On track to meet expectations
- with  $2000 \text{ pb}^{-1}$  expect  $\delta M_W(\text{CDF}) = 25 \text{ MeV}/c^2$

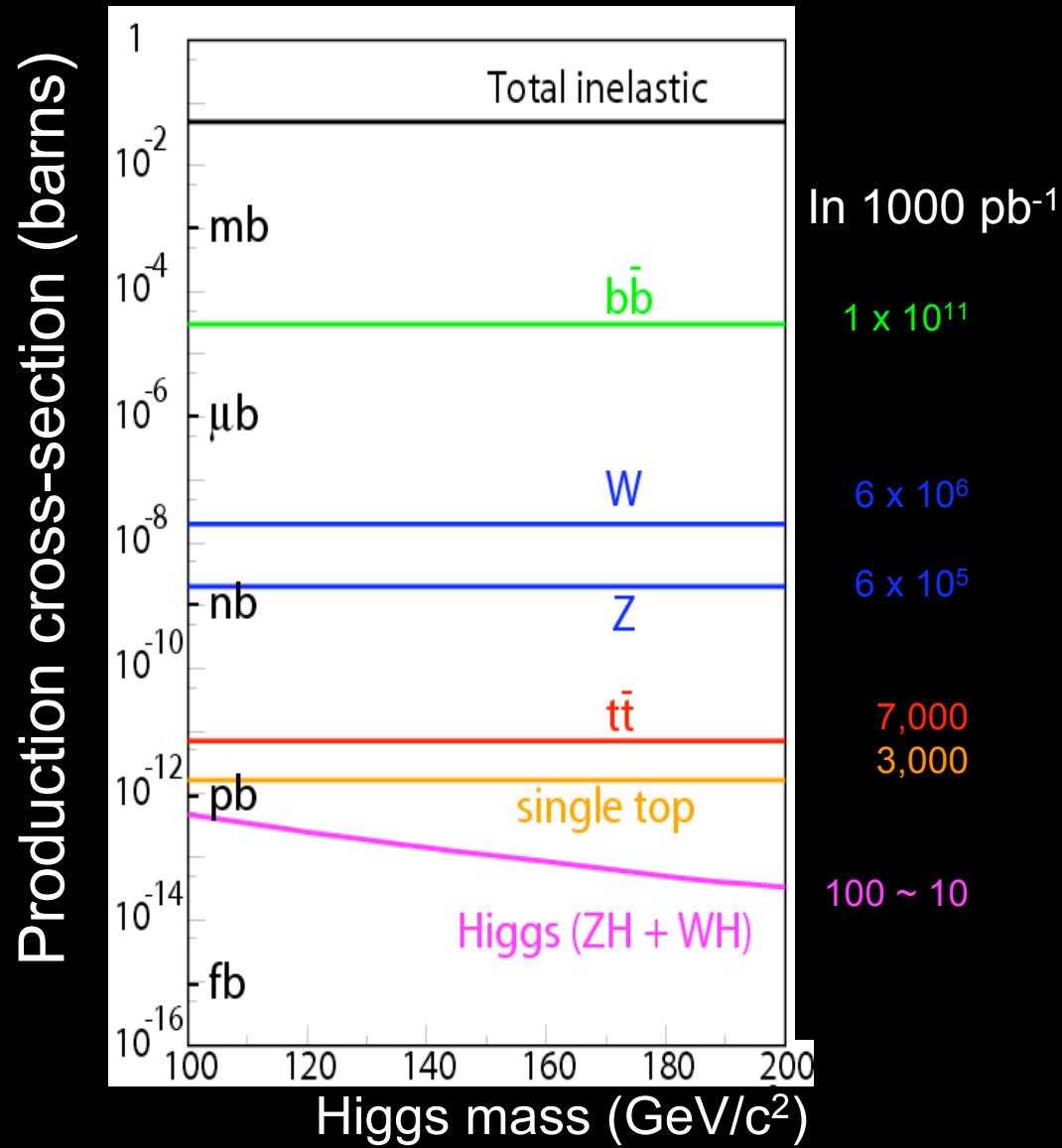
# Constraints from $M_W$ and $M_t$



- Prefers light higgs... where Tevatron sensitivity is best

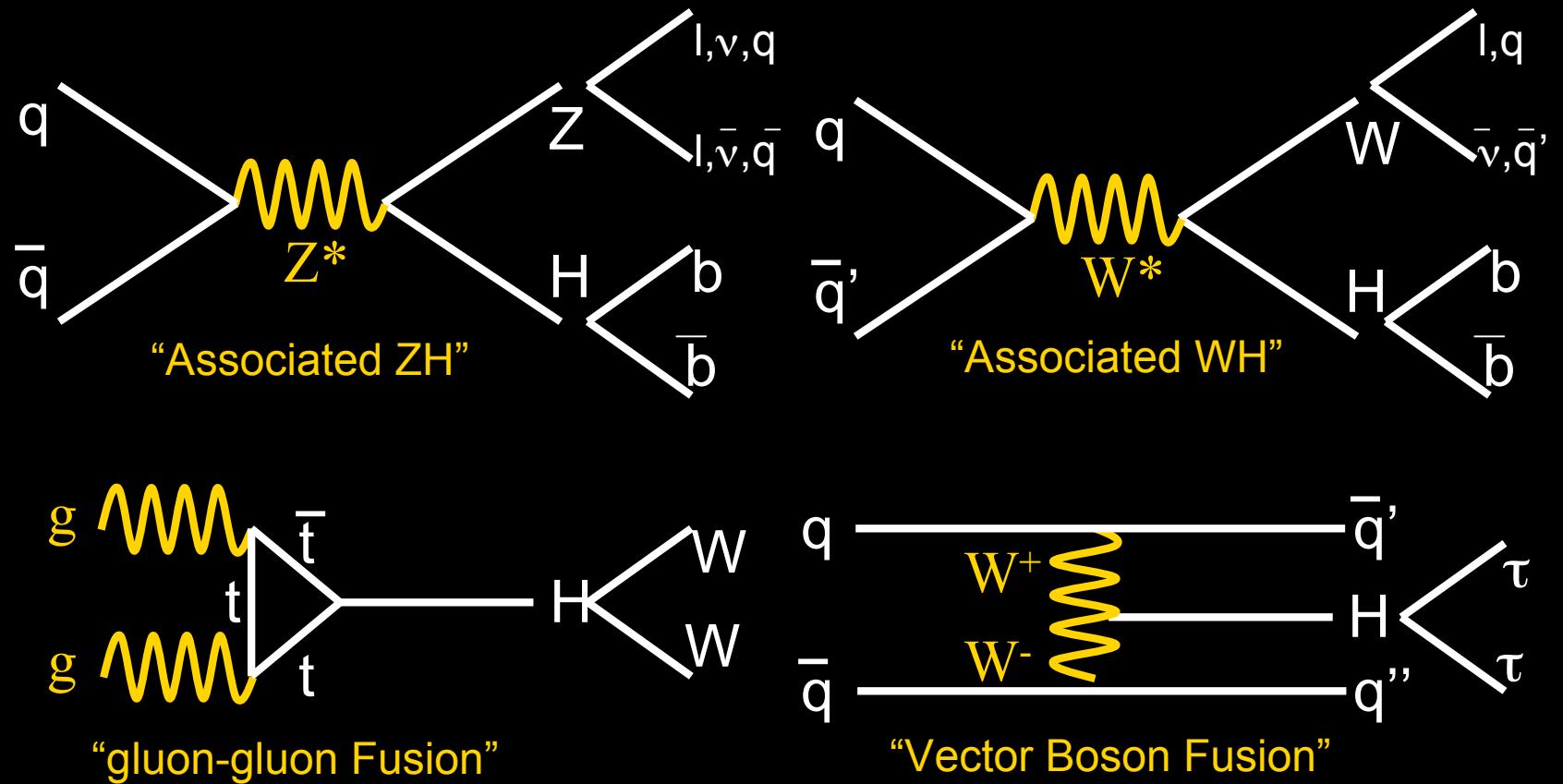
# Searching for the SM Higgs

# Searching for the SM Higgs



- Higgs produced **very rarely**

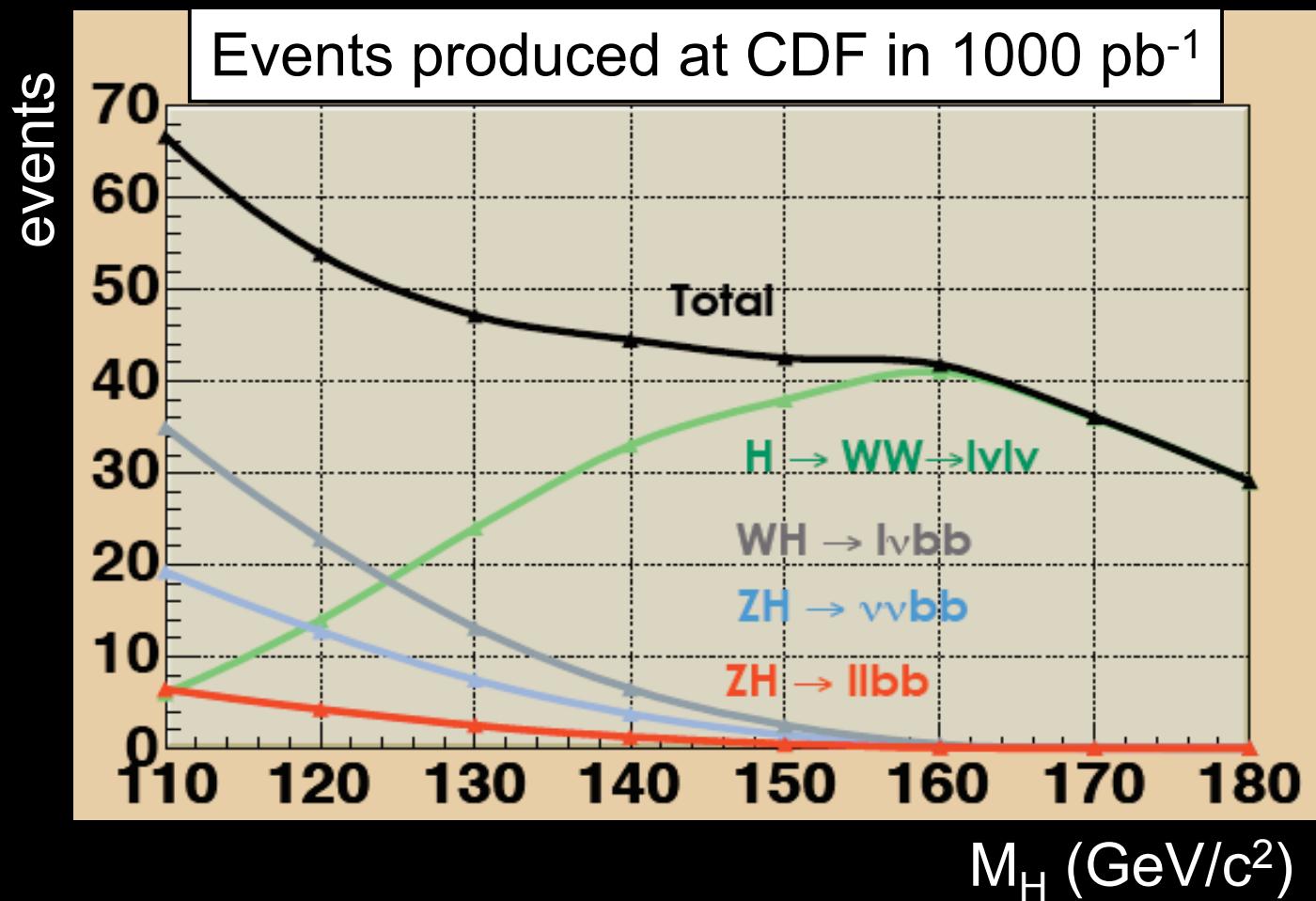
# Searching for the SM Higgs



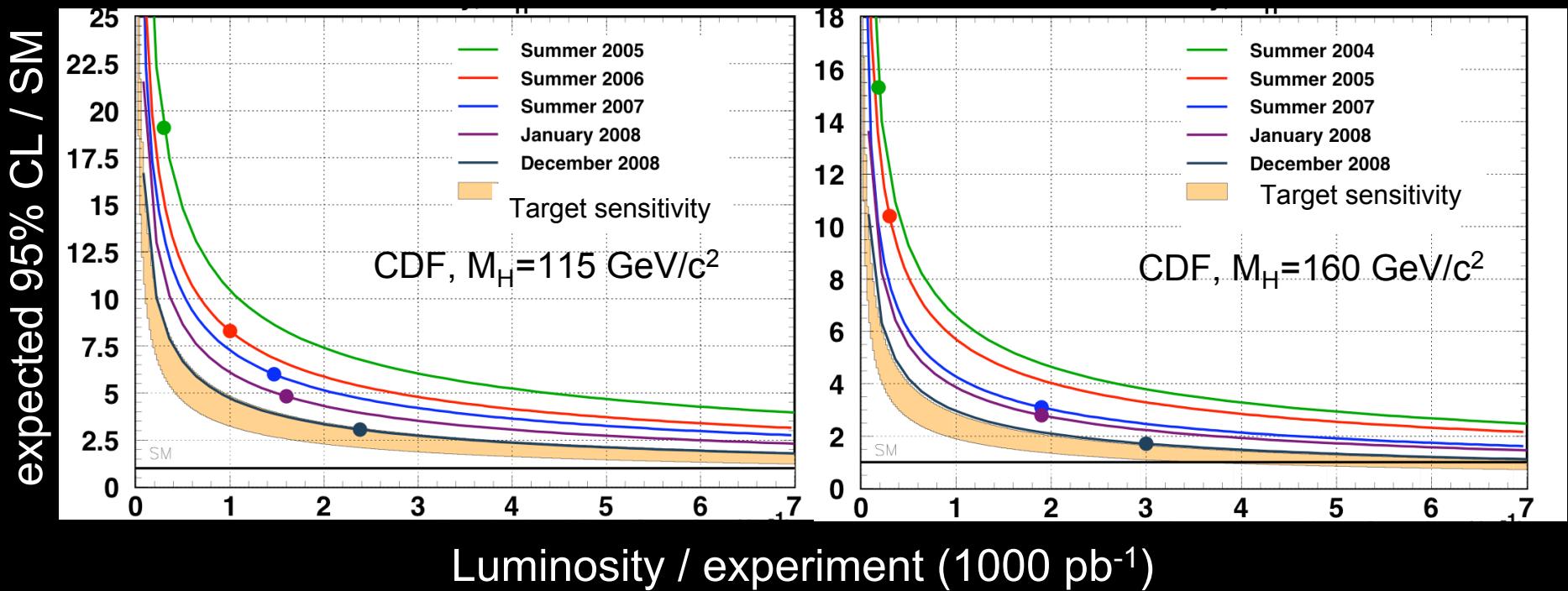
- We use all available production mechanisms  
... and multiple decay final states

# Searching for the SM Higgs

- To reach necessary sensitivities, need to combine all of them together, plus CDF+D0



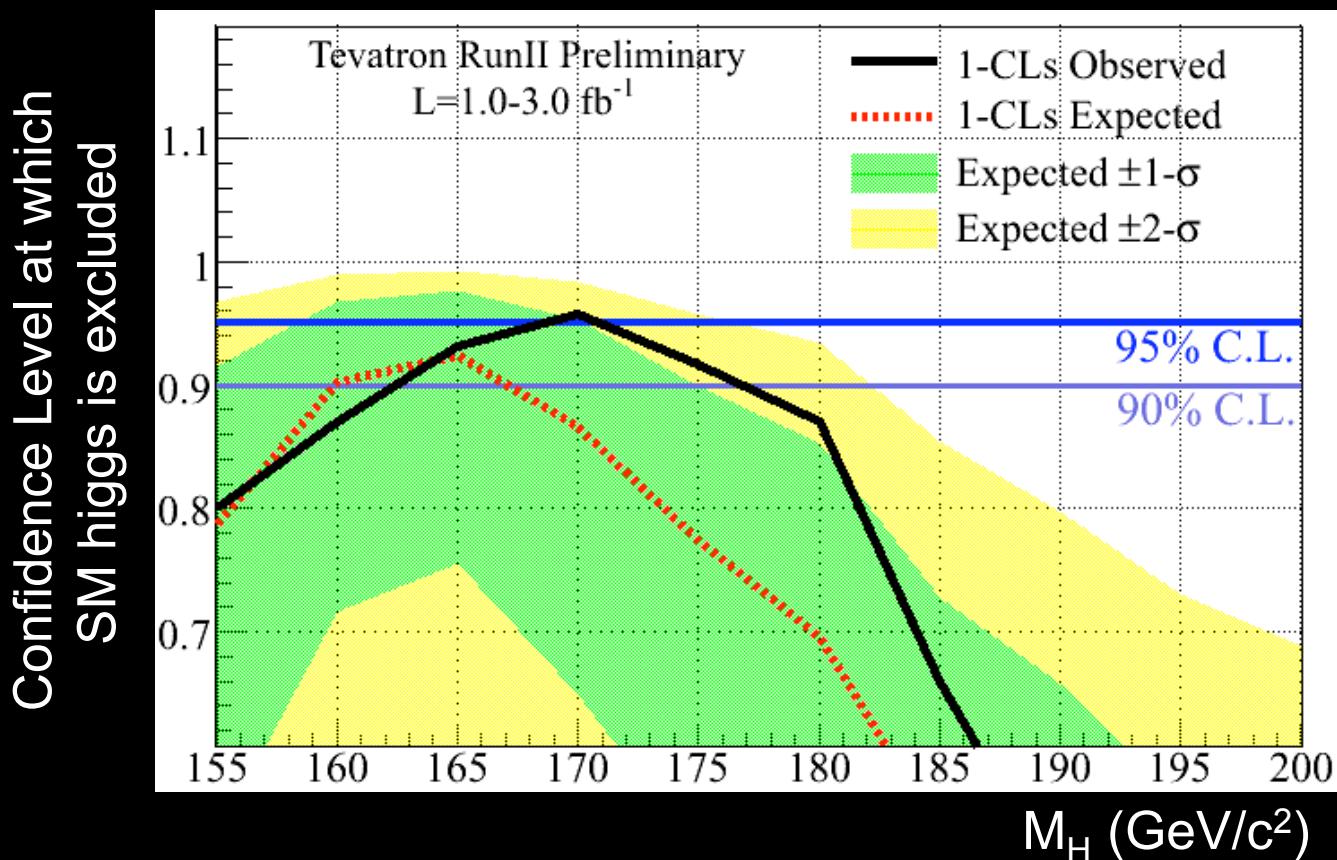
# SM Higgs Results



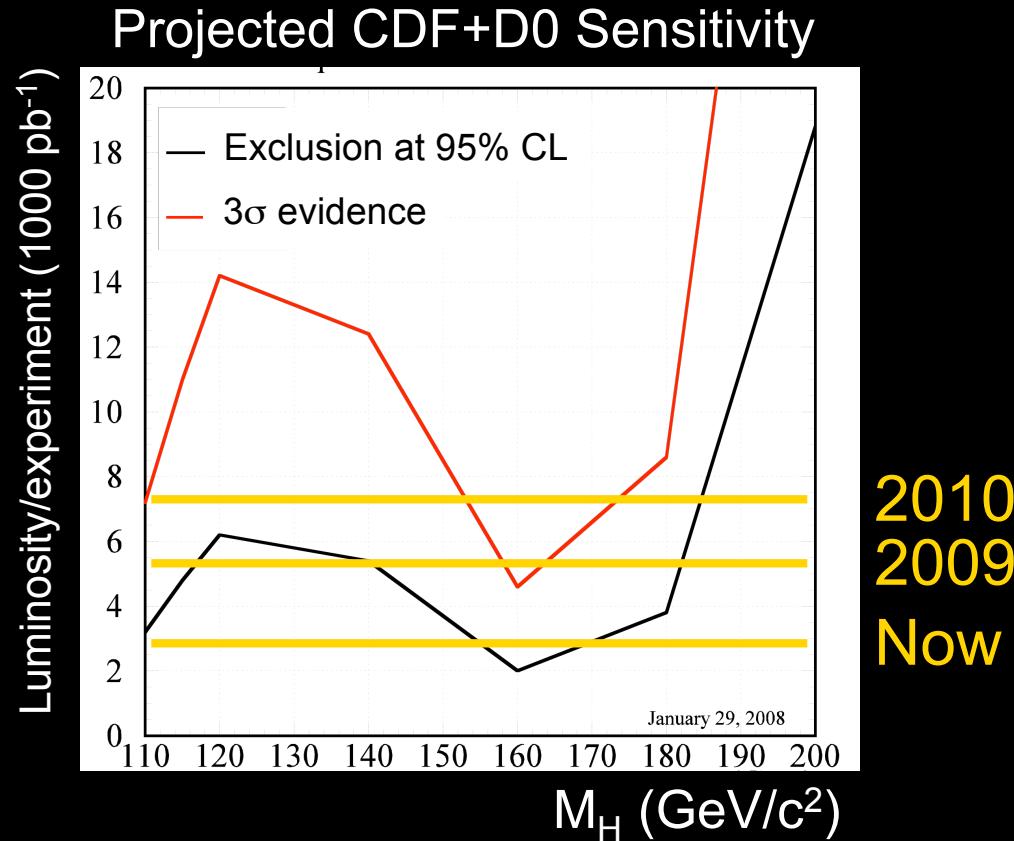
- We are just starting to reach SM sensitivities
  - Continually improving
  - Combination with D0 important, especially at low mass

# SM Higgs Results

- After combining CDF+D0
  - Exclude  $162 < M_H < 177 \text{ GeV}/c^2$  @ 90%CL



# SM Higgs Prospects

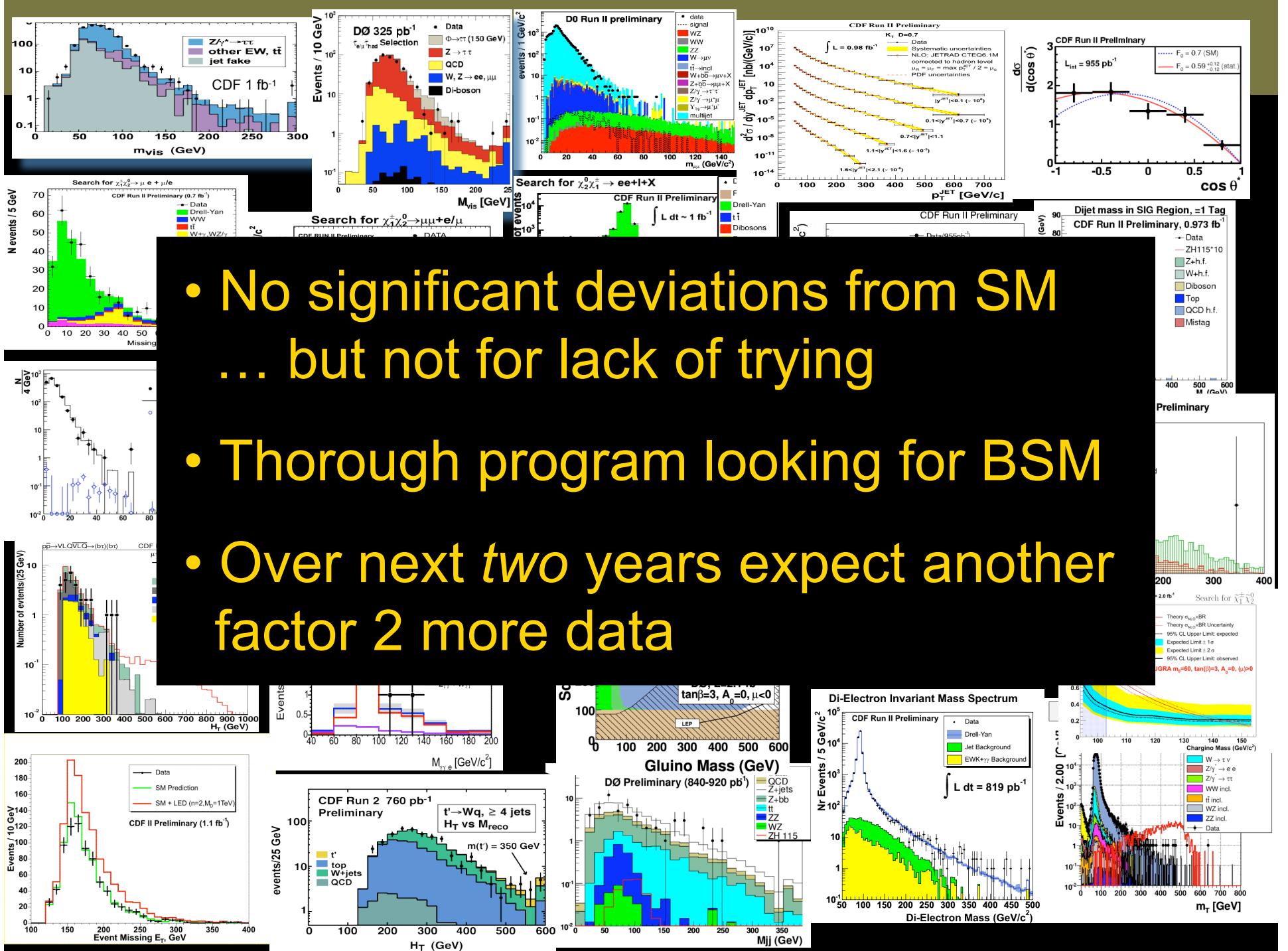


- With 7000-8000  $\text{pb}^{-1}$  dataset expect
  - to exclude all  $M_H < 180 \text{ GeV}/c^2$  @ 95%CL
  - or obtain 3 $\sigma$  evidence if  $155 < M_H < 170 \text{ GeV}/c^2$

# Searching for BSM Physics

# Searching for BSM Physics

Occupying the energy frontier means the Tevatron experiments have the world's best sensitivity to many different Beyond the Standard Model theories



- No significant deviations from SM  
... but not for lack of trying
- Thorough program looking for BSM
- Over next *two* years expect another factor 2 more data

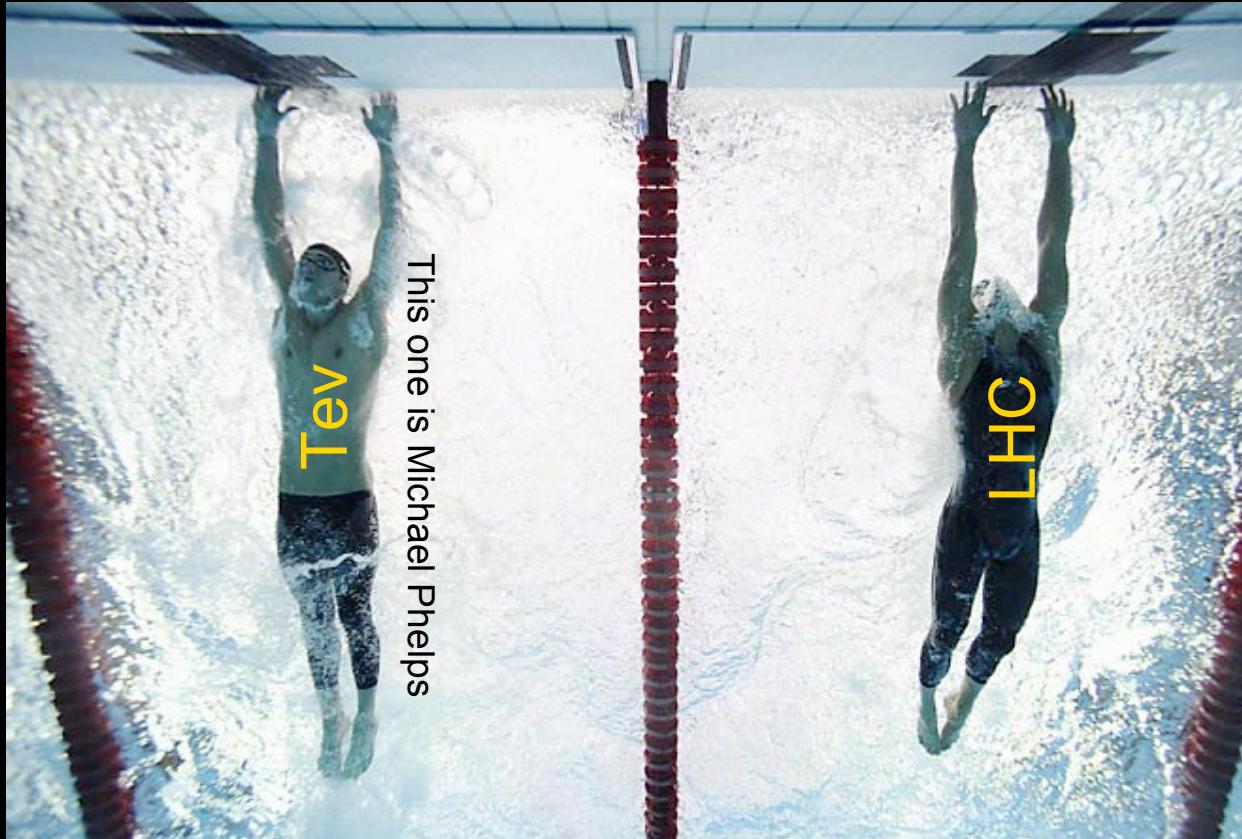
# Summary

- Tevatron has provided the world's most energetic collisions for the last 25 years
- The Tevatron physics program is rich and broad, producing 1 publication / 5 days
  - Latest results:  
<http://www-cdf.fnal.gov/physics/S08CDFResults.html>  
<http://www-d0.fnal.gov/Run2Physics/ICHEP08/S08D0Results.html>
- The LHC is set to begin collisions at 7x the Tevatron energy in the coming year

# Tevatron Legacy

- The LHC will inherit from the Tevatron
  - Precision determination of  $\Delta m_s$  and constraints on BSM contributions to the  $B_s$  system
  - Precision determinations of  $M_W$  and  $M_t$   
(may be hard for LHC to surpass)
  - More stringent constraints on a wide variety of BSM theories

# Tevatron Legacy



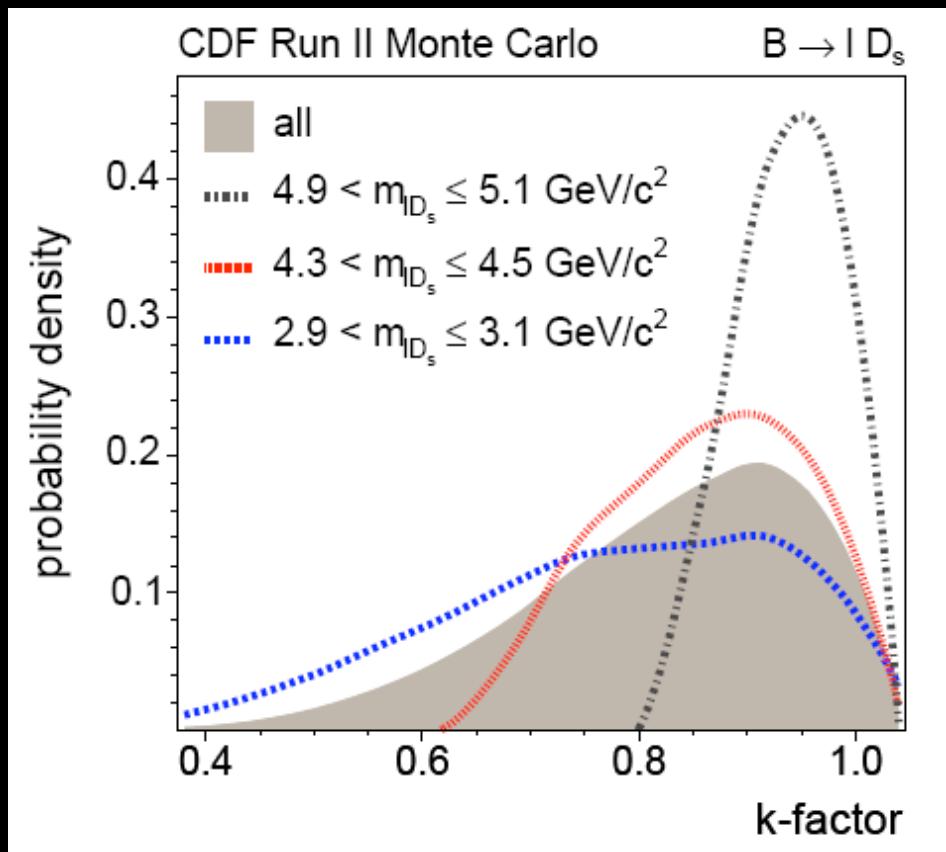
This one is Michael Phelps

– A higgs mass

# Backups

# $B_s$ Mixing

- Determine proper decay time from final state

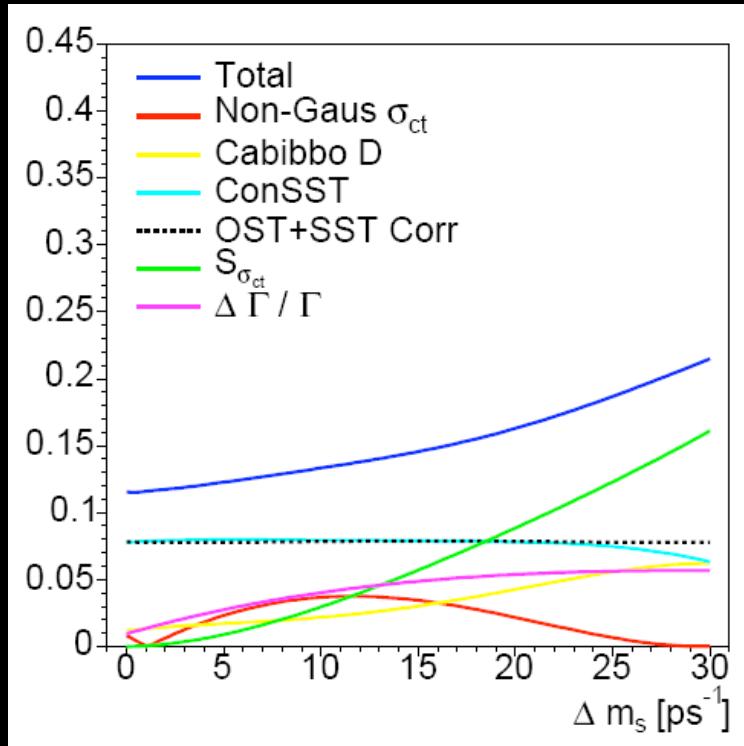


$$\tau = \frac{L_T M_{B_s}}{P_T^{vtx}} K$$

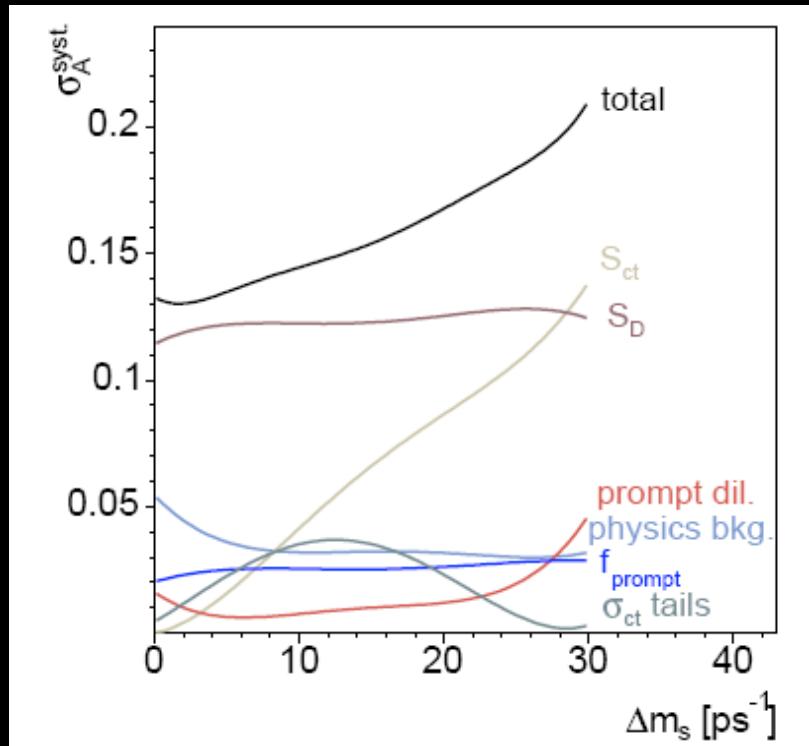
$\kappa$  determined from Monte Carlo (MC) simulation

# $B_s$ Mixing: Systematic Uncertainty

## Hadronic

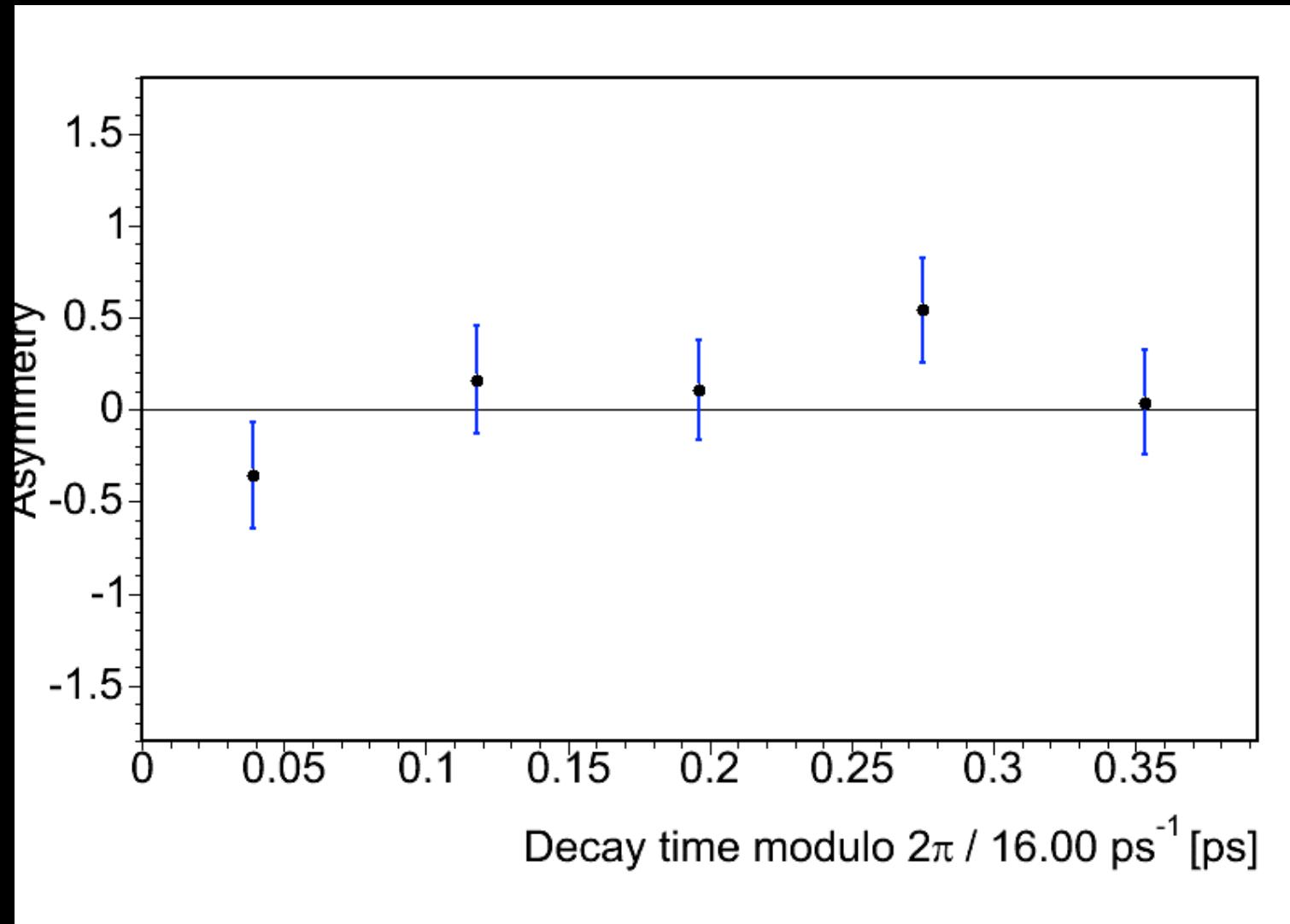


## Semileptonic

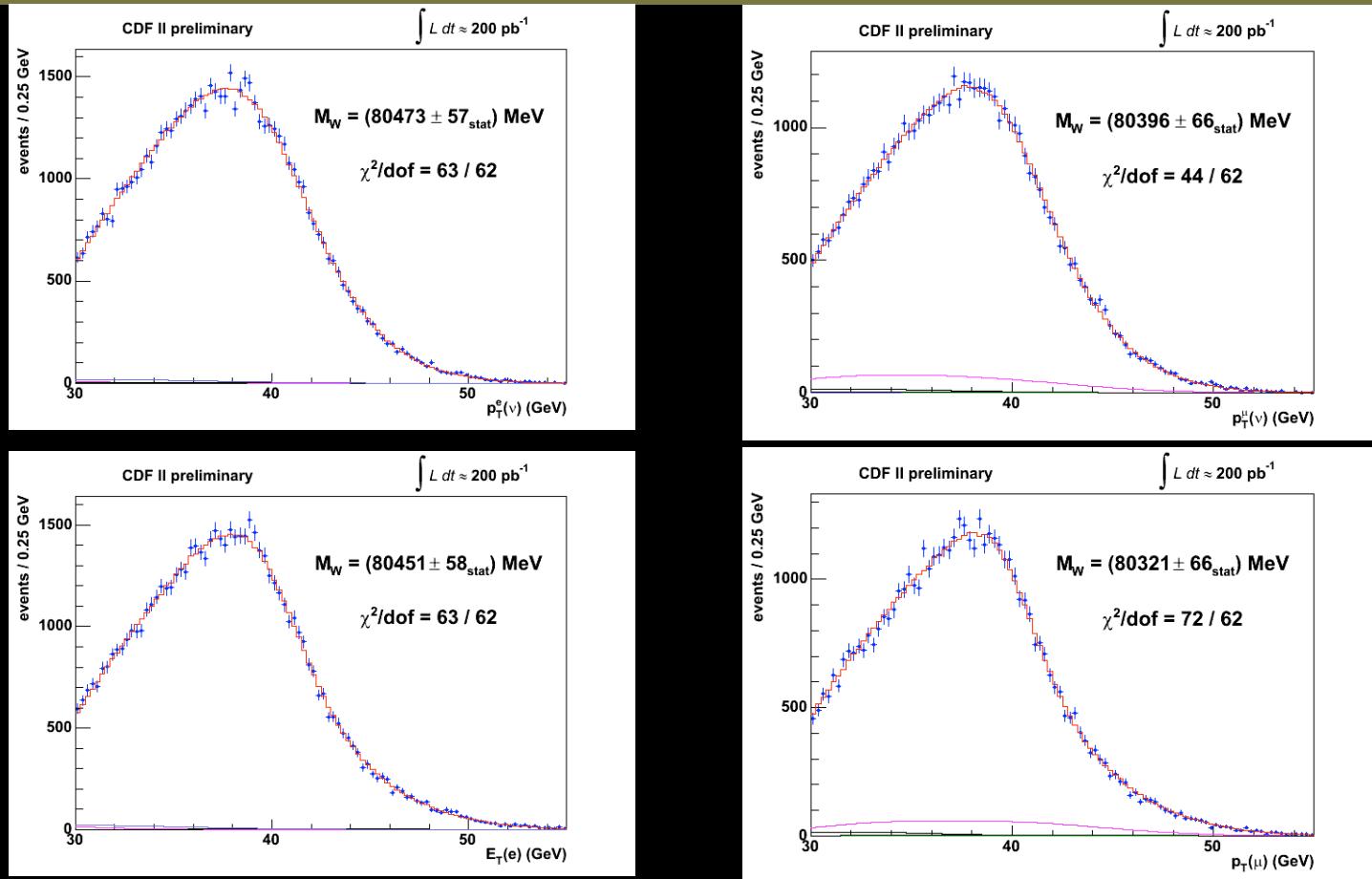


- **Systematics on Amplitude, relevant only when setting limits**
  - Largely cancel in  $A/\sigma_A$ ; included in lhood to determine significance
  - Systematic uncertainties are very small compared to statistical
  - All these irrelevant when measuring  $\Delta m_s$

# B<sub>s</sub> Mixing

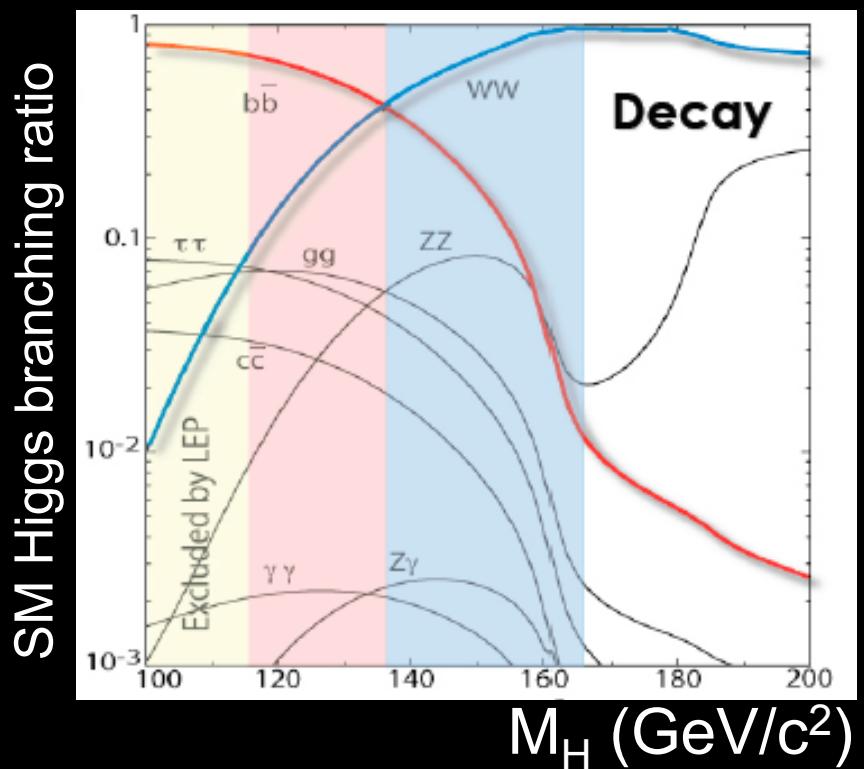
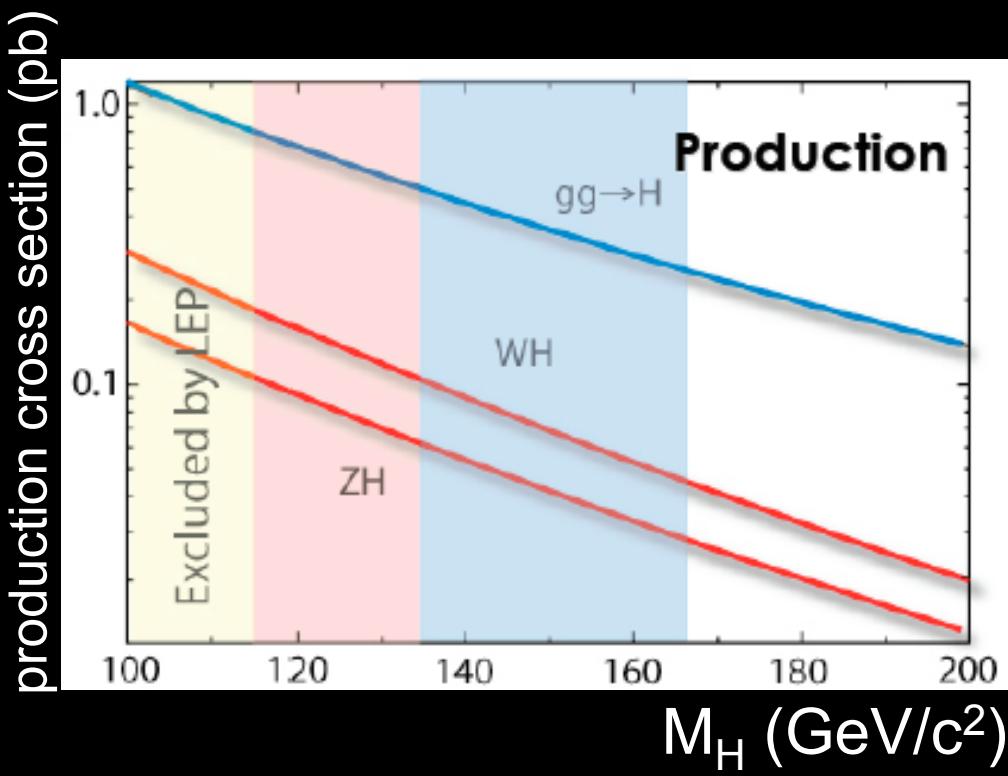


# $M_W$ Results



- CDF result combination of 6 different fits
  - $m_T$ ,  $p_T(\text{lepton})$ ,  $p_T(v)$  have differing systematic sensitivities

# SM Higgs Production and Decay



- Low mass:  $WH$ ,  $ZH$  with  $H \rightarrow b\bar{b}$
- High mass:  $ggH$  with  $H \rightarrow WW$

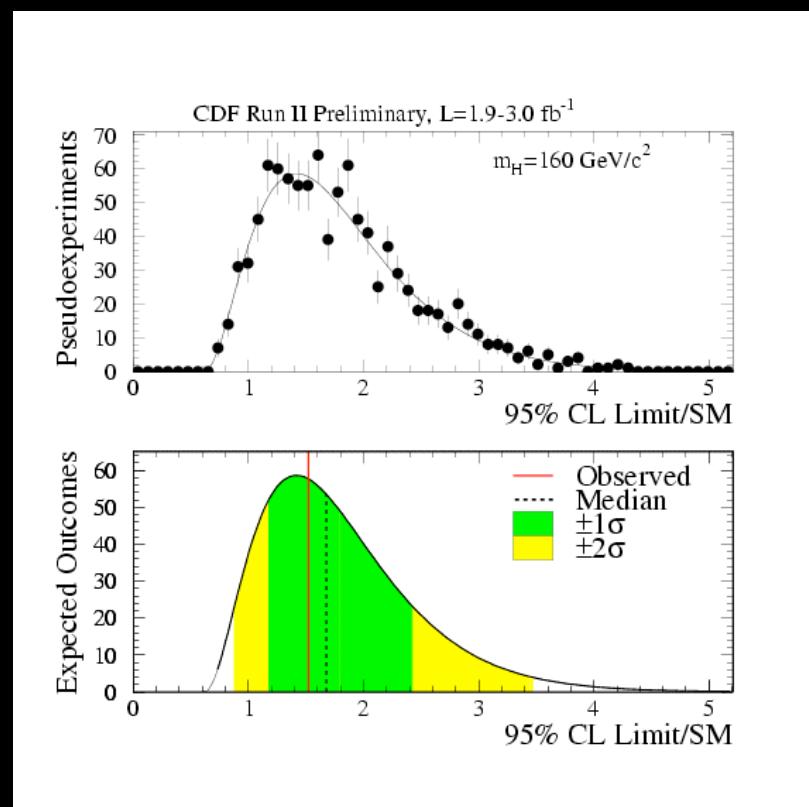
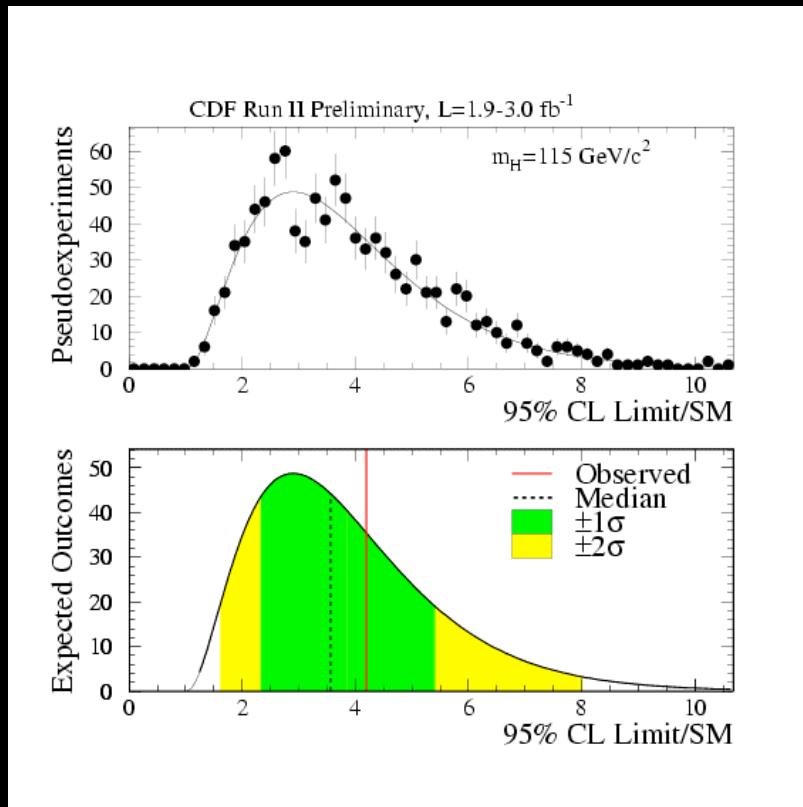
# SM Higgs Results

$m_H$ (GeV/ $c^2$ )	Observed limit/SM	$-2\sigma$ expected	$-1\sigma$ expected	median expected	$+1\sigma$ expected	$+2\sigma$ expected
100	3.01	1.43	2.07	3.13	4.78	7.10
105	2.87	1.30	1.91	2.98	4.62	6.95
110	3.34	1.47	2.15	3.29	5.00	7.35
115	4.19	1.58	2.32	3.56	5.43	8.05
120	4.53	1.93	2.75	4.15	6.29	9.31
125	6.04	1.87	2.77	4.29	6.55	9.72
130	5.62	1.99	2.80	4.21	6.38	9.46
135	5.40	1.58	2.29	3.52	5.42	8.12
140	5.45	1.48	2.20	3.41	5.23	7.79
145	3.92	1.33	2.02	3.11	4.71	6.90
150	4.13	1.12	1.65	2.60	4.08	6.20
155	2.27	1.19	1.63	2.30	3.24	4.52
160	1.52	0.86	1.17	1.68	2.43	3.50
165	1.64	0.80	1.12	1.60	2.26	3.13
170	1.80	0.98	1.33	1.90	2.73	3.88
175	1.97	1.22	1.63	2.35	3.45	5.03
180	2.52	1.35	1.89	2.74	3.95	5.60
185	4.47	1.90	2.64	3.81	5.48	7.76
190	5.47	2.15	3.11	4.54	6.50	9.09
195	9.05	2.64	3.62	5.33	7.94	11.63
200	10.18	2.92	4.15	6.19	9.22	13.44

- From latest CDF results

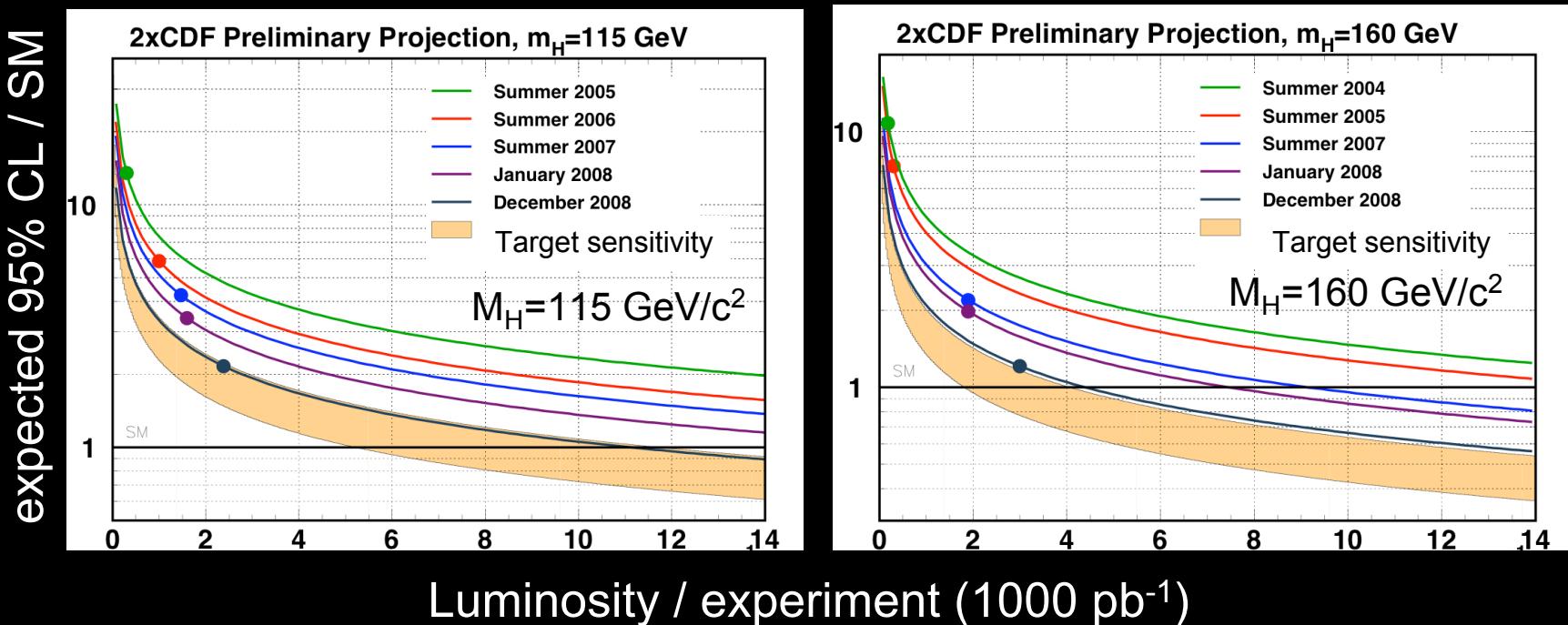
# SM Higgs Limits

- The variations are from stat fluctuations in signal and background
  - Any given experiment can be lucky or unlucky



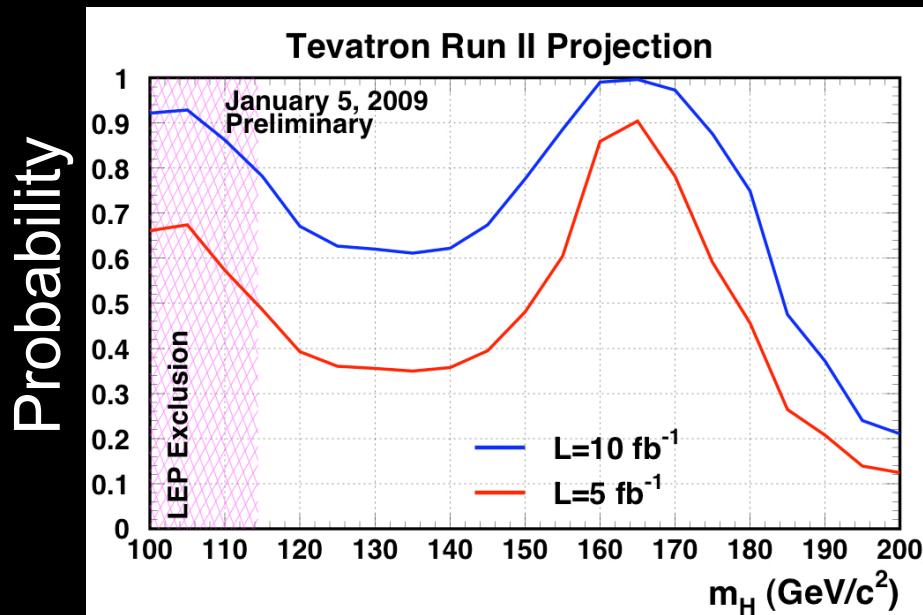
# SM Higgs Limits

- Tevatron Projections
  - Assumes CDF/D0 have same sensitivity
  - So far this has been the case

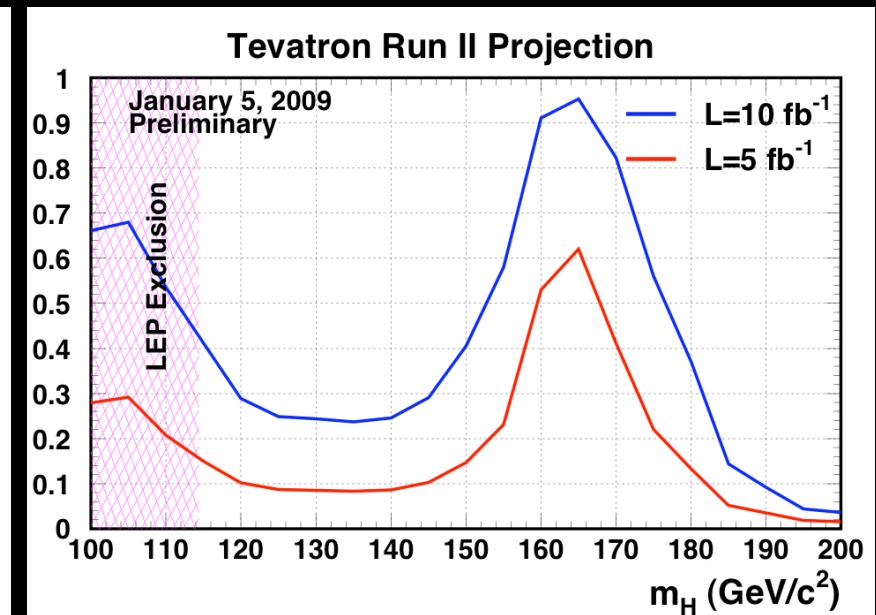


# SM Higgs Sensitivity

95% CL exclusion

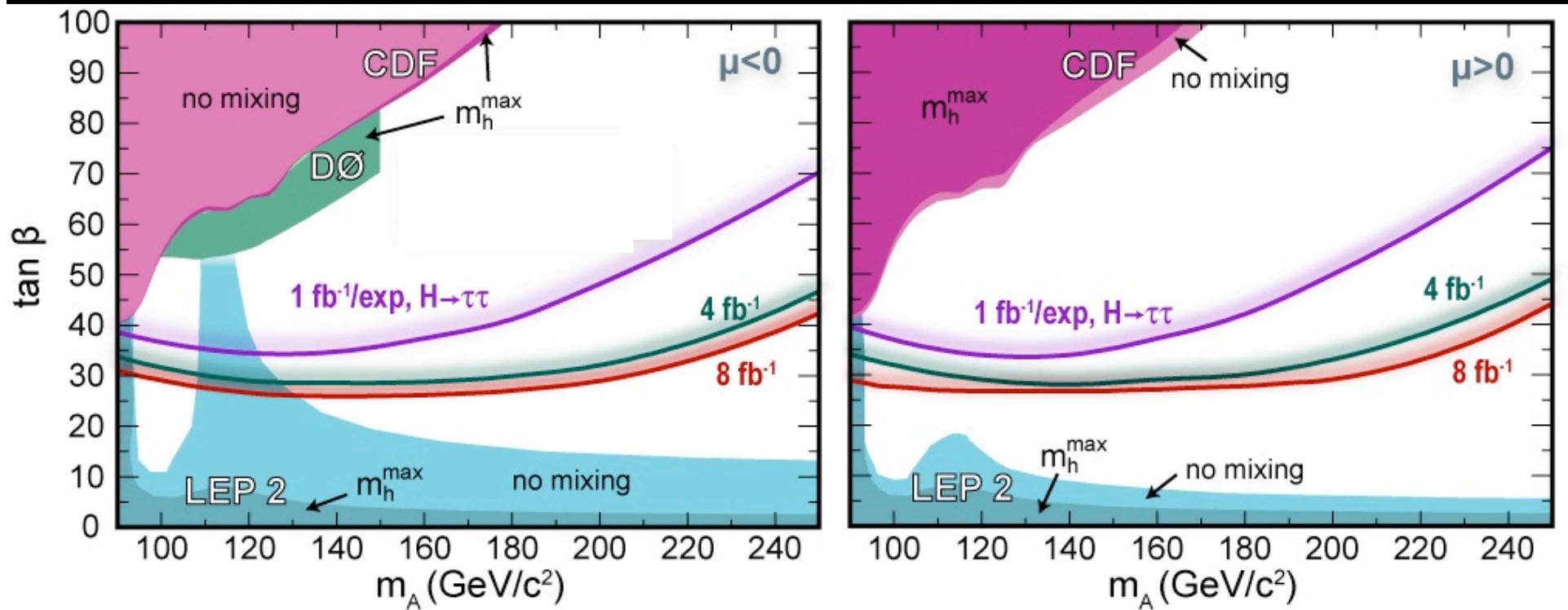


3 $\sigma$  Evidence



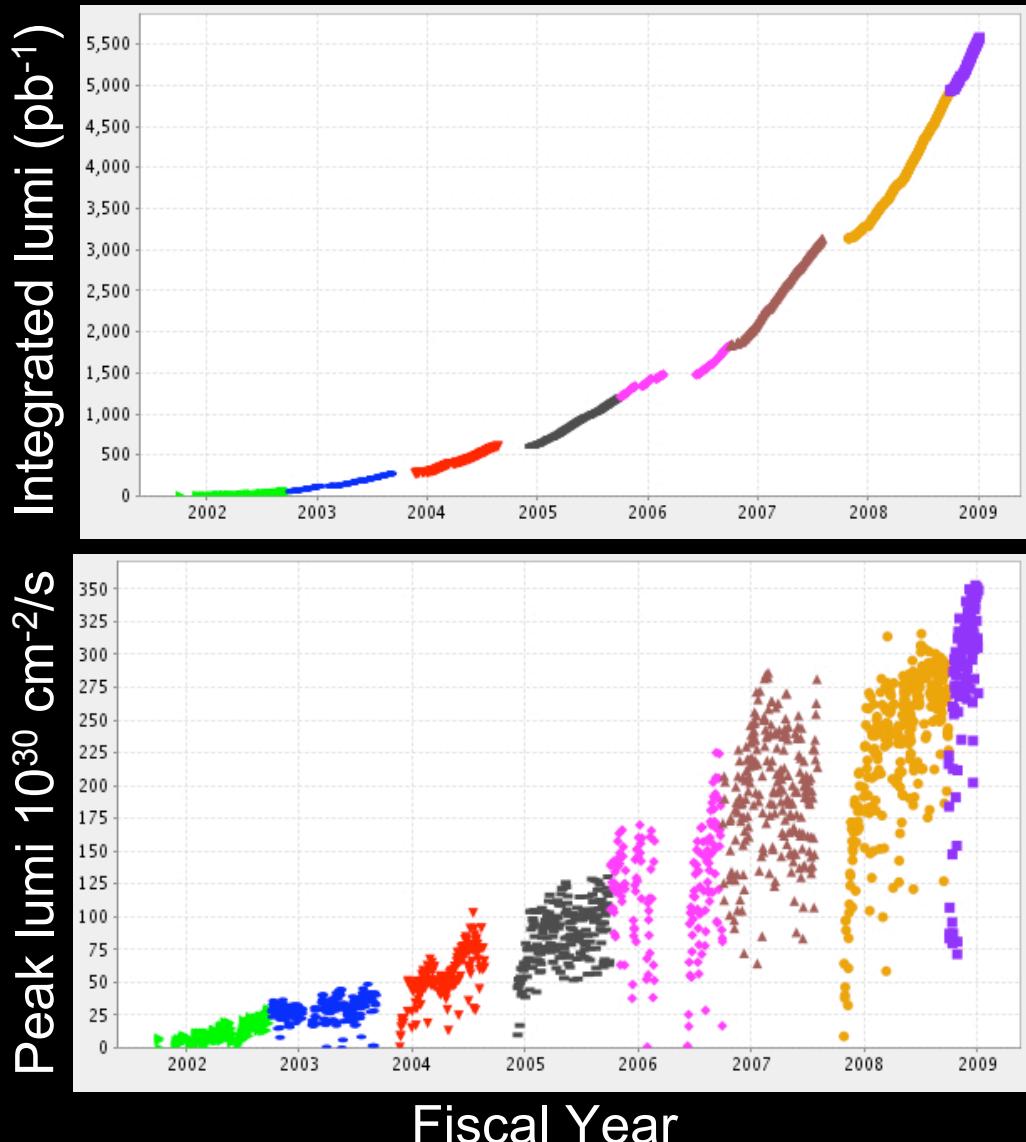
- Additional data buys you reach and “luck”

# MSSM Higgs Sensitivity



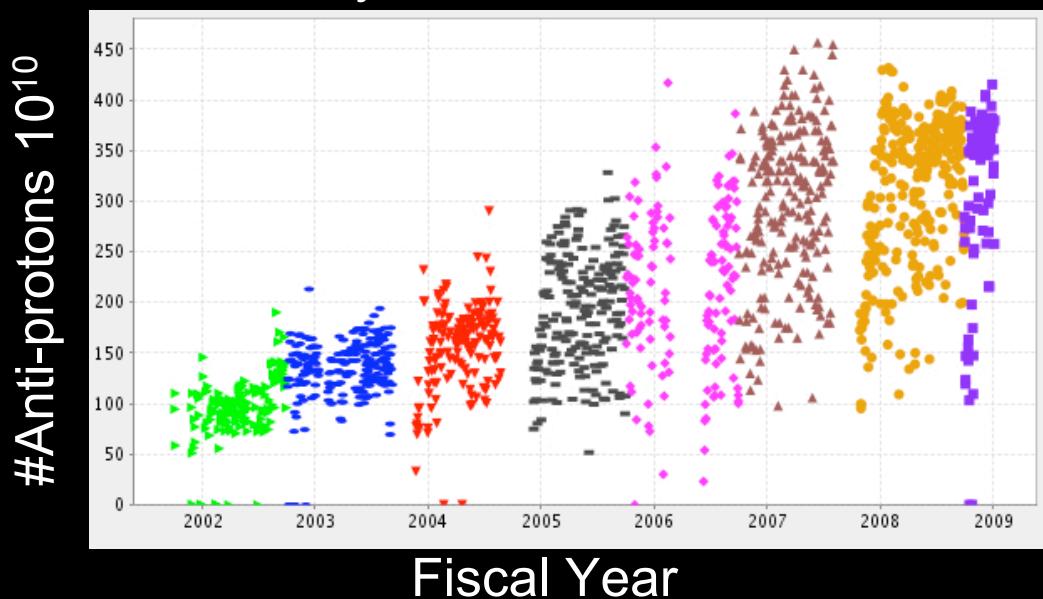
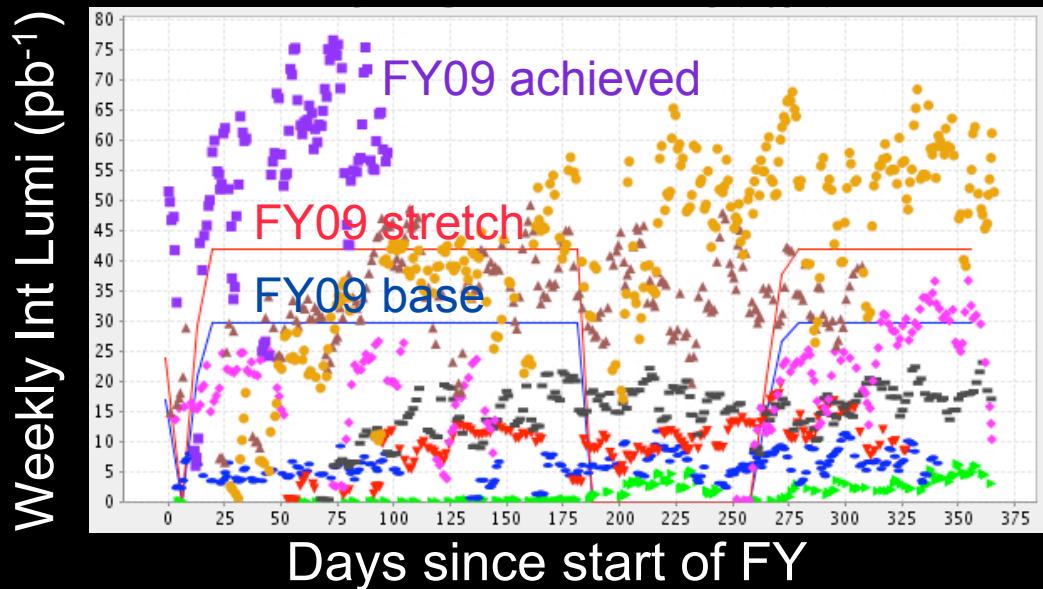
- Sensitivity for all  $M_A < 200 \text{ GeV}/c^2$  for  $\tan \beta > 30$

# Tevatron Performance



- Better than ever
- Exceeding Run II design goals
- On track for  $8 \text{ fb}^{-1}$  delivered per experiment by end FY2010

# Tevatron Performance



- Anti-proton stack rates fastest ever
- Anti-protons in collision and complex up-time best ever
- Weekly integrated luminosity best ever